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Aviation Gasolines and Future Alternatives

Donald J. Patterson, *Editor*
University of Michigan
Ann Arbor, Michigan

Proceedings of a workshop held at
Lewis Research Center
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National Aeronautics
and Space Administration

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PREFACE

It is a well recognized fact that the vast majority of the world's civil aircraft are powered by gasoline piston engines of U.S. manufacture. These planes are certified to use only aviation gasoline (avgas) for fuel. In the past several years, avgas has become a distinct problem in such respects as shortages, unavailability, and rapidly rising prices. In view of the unstable world oil supply/demand situation and the continuing price control attempts of OPEC, the aviation gasoline problems can be expected to persist. Simple or short term solutions are not foreseen. In the longer run, however, there are encouraging possibilities in such areas as: improving the fuel economy of conventional gasoline engines; better overall efficiency from expected aerodynamic and structural advances; and the probable emergence of alternative light-aircraft powerplants (e.g., diesels, small turboprops) which can burn less expensive and more readily available fuels.

The purpose of this workshop was to explore possible technical developments that may contribute to an overall solution of the light-aircraft fuel and energy problems. The intent was not to disseminate new information, but rather to clarify issues and identify needed actions. Various technical, legal, political, and economic issues were brought forth and useful areas of technical work for future government-sponsored technology programs were identified.

In order to cover all aspects of "Aviation Gasolines and Future Alternatives," the invitation list was drawn up with a view toward both expertise in specific subjects and breadth of knowledge and experience across the general aviation field. Participants were encouraged to take an active role both as contributors to their areas of specialization and also to the general discussions. By bringing together representatives from government, industry, research, and academic organizations, it was hoped that a greater understanding of the overall aviation fuel situation would emerge.

The meeting was organized by Dr. Edward Willis of NASA and chaired by Mr. John W. Olcott, Editor of Business and Commercial Aviation Magazine. The 70 attendees were from NASA; FAA; the major general aviation airframe, engine, and supplier organizations; the oil refining industry; GAMA; NATA; AOPA; EAA; and various research and academic organizations.

To help structure the two and one-half day workshop, participants were asked to address four major topics within a time frame of 5 to 20 years, a longer range viewpoint covering the remainder of this century. These topics were:

1. Define the fuel requirements (type/quantity) of the future general aviation fleet.

2. Define the "most likely" and "limiting-case" scenarios for future avgas and other general aviation fuels availabililty, composition, and distribution trends.

3. Identify and rank technologies that would help reconcile supply and demand.

4. Recommend the most needed specific programs, and define the proper government role and mode of operation relative to these programs.

The workshop was divided into working sessions, each of which addressed one of the four major topics. The working sessions and their chairman were:

Session 1: General Aviation Industry Needs and Directions
- Stanley Green, GAMA

Session 2: Fuel Supply/Demand/Distribution Issues
- Kurt Strauss, Texaco

Session 3: General Aviation Technology Prospects
- Donald Patterson, University of Michigan

Session 4: Near-Term and Ongoing Technology Programs
- Harry Johnson, NASA

To begin the workshop, a number of prepared statements were presented in each of the four areas. These comprised the first day, and half the morning of the second day. For the balance of the morning of the second day, the attendees divided into four smaller working-committee groups corresponding to the topics indicated above. These group meetings were informal and no transcripts of the proceedings were made. However, an informal summary of the discussions was provided to the Workshop Chairman by each of the four working-committee chairmen. The balance of the meeting involved the preparation of an overall summation of the workshop. This summation integrated the prepared statements, the informal summaries of the chairmen of the four working committees, and additional comments from the workshop attendees. This summation was written by Mr. John Olcott, Chairman of the workshop.

The present report includes all the prepared statements together with the chairman's summation. Some editing was required to clarify the oral presentations as they were reduced to writing. In editing, every effort was made to preserve the intent of the speaker and the emphasis with which he addressed the subject.

WORKSHOP SUMMARY

John W. Olcott
Chairman of the Workshop
Editor of Business and Commercial Aviation Magazine

INTRODUCTION

After two days of presentations and discussions pertaining to the impact of fuel on the technology of propulsion for general aviation, the attendees of NASA's Technical Workshop on Aviation Gasolines and Future Alternatives, held February 3, 4, and 5, 1981, made several observations, conclusions and recommendations.

OBSERVATIONS

A workshop on fuels and their impact on the development of general aviation powerplants was an appropriate undertaking for NASA. The occasion provided an excellent opportunity to hear and debate the positions of knowledgeable representatives from the producers of petroleum products, aircraft and engine manufacturers, aircraft fixed base operators, users of general aviation and members of the research community. In addition to providing NASA with recommendations for meaningful research pertaining to propulsion, the workshop served a valuable informational function due to the different perspectives that members of the aviation community brought to the forum. A constructive cross-fertilization of ideas resulted from the program.

Members of the workshop observed that general aviation provides essential functions for business throughout the United States and the world. Business travelers who need to move rapidly between smaller cities or who must travel to several cities during the same day find that airline service frequently is not available or is inappropriately scheduled to satisfy their requirements. With the continuing rise in fuel prices and the advent of airline deregulation, the major air carriers have concentrated their schedules between city pairs that are separated by long distances and are sufficiently large to generate high load factors. Such flights yield the highest profits for the airlines. Commuter airlines have not completely filled the gap in service. Consequently, general aviation has become an integral part of the nation's transportation system, and its importance will increase as the airlines continue to react to the rising costs of fuel and labor.

In addition to being a time-efficient form of transportation, general aviation also is fuel-efficient. If the same travel capability that now is available with small general aviation equipment were provided by airlines, more fuel would be consumed.

Another important factor is the role general aviation products play in the U.S. balance of payments. The U.S. sells more products throughout the world's general aviation community than does any other nation, and we enjoy the number one position in exports of general aviation goods. But this U.S. dominance is being challenged. Only by offering products that embody the most advanced technology and offer the most

desired features, such as high fuel efficiency, low life cycle costs and high reliability, will the U.S. maintain its leadership in world markets.

The optimum powerplant for general aviation aircraft is one that provides desirable performance while using a readily available fuel and operating for the lowest possible cost per mile.

Participants at the workshop concurred that the most readily available aviation fuel for the next 30 years will be a product that meets the specification of ASTM D1655 or its future derivatives. That consensus is based upon the extensive use of such turbine fuel by the world's major airlines, thereby being readily available at major airports. The turbine fuel that airlines normally use is more easily refined and distributed than is aviation gasoline. Also, considering the long term sources of aviation fuel, attendees noted that turbine fuel can be synthesized from shale with good efficiency.

The workshop participants agreed, in general, that the availability of aviation gasoline during the next 20 to 30 years will be constrained by marketing and distribution considerations rather than by refining capability. In markets where there is a strong demand for aviation gasoline, it will be available. But at outlying airports where flying activity is sparse or the normal consumption of fuel is low, petroleum dealers are finding the distribution of aviation gasoline to be uneconomical. Therefore, shortages or lack of availability may be prevalent at smaller airports in the future.

Furthermore, the availability of aviation gasoline has been limited or interrupted in several foreign countries, due mainly but not exclusively to the problems that have occurred within Iran.

While the majority of the workshop participants felt that the fuel needs of general aviation would be met adequately with aviation gasoline and airline-type turbine fuel, a minority group felt that flying in remote areas would be seriously hindered unless the use of automotive gasoline in aircraft was approved. Consequently, they wanted NASA to pursue a research program that would develop technical information relevant to the safe use of automotive gasoline in present and future aircraft reciprocating powerplants and fuel systems. Parts of that program would include identifying the limits for using automotive gasoline, examining the effects of aromatic variability on elastomers and possibly developing portable, easy to use devices for measuring the properties of gasoline.

The majority of the workshop attendees were against the aviation use of automotive gasoline because of the possible problems associated with the wide variation in its properties relative to the needs of general aviation.

CONCLUSIONS

1. Although there appear to be many questions concerning the use of automotive gas in aircraft, the majority of the workshop attendees did not feel that NASA is the appropriate agency to generate relevant information in this area, since work to be done is of an applications nature and the results would differ according to the specific engine and aircraft considered. The majority of the workshop attendees felt that the tradeoff between potential problems, such as the variability of automotive gas and the

specter of product liability, when compared with the possible rewards of approving the use of such fuel in aircraft, did not provide sufficient incentive to commit NASA's or another Federal agency's funds to a research program. However, the attendees did not wish to preclude the use of private funds for such investigations if some manufacturer or user desired to seek approval for using automotive gas in aircraft.

2. There is no advantage to the manufacturer, distributor or consumer in changing the characteristics of aviation gasoline in a manner that would require recertification of existing engines.

3. The composition of the general aviation fleet will be dominated by gasoline-fueled reciprocating engines for the next 30 years, with significant numbers of such aircraft remaining in use well beyond that period of time.

4. A need exists to enhance the capabilities of gasoline-fueled reciprocating engines, particularly in the area of altitude performance, fuel consumption, noise, cooling, reliability, weight, size and ease of operation.

5. A need exists to develop simplified and more convenient methods of testing aviation fuels.

6. The fuels to be used for researching and developing future general aviation engines should match the specifications for aircraft gas turbine fuels, which means ASTM D1655 or its derivatives. The suitability of such a fuel should be established by parametric studies of pertinent fuel properties. However, the fuel ultimately should be identical to the fuel used by large commercial gas turbine engines for aircraft.

7. A need exists for an intermittent combustion engine that is optimized to operate with the type of turbine fuel that is in most widespread use by the airlines. It would be desirable if such engines could operate on aviation gasoline. While such an engine might be classified as possessing a multi-fuel capability, that feature is of secondary importance and should not be allowed to compromise the design. Also, the engine should have a form factor that allows it to be easily retrofittable to aircraft powered by gasoline-fueled reciprocating engines, and it should possess better specific fuel consumption, lower life cycle costs and less weight per horsepower than existing intermittent combustion engines.

8. Although the workshop concentrated on intermittent combustion powerplants, NASA should continue to pursue the objectives of its General Aviation Turbine Engine Program since turbines have their own place in the general aviation market.

RECOMMENDATIONS

1. That NASA not undertake research that is intended to modify the properties of aviation gasoline.

2. That NASA consider a research program that would lead to the development of simplified and convenient methods for testing aviation fuels, with specific emphasis on the measurement of the rich rating.

3. That NASA proceed with and accelerate its Piston Engine Technology (PET) Program since the results of that effort will benefit existing gasoline-fuel engines as well as future intermittent combustion engines whether they are of the compression or spark ignition type and use reciprocating or rotary combustion techniques. The attendees emphasized that the results of PET would have an immediate application, would benefit engine types that will be operating for the next 30 or more years, and are needed now.

4. That NASA proceed with a research program that will result in the enabling technologies needed to develop a general aviation powerplant that runs efficiently on the type of turbine fuel that is in most widespread use by the airlines. The engine, which is described in Conclusion 6, could use either compression or spark ignition and either reciprocating or rotary combustion. Furthermore, except for the form factor, it might be a gas turbine although the recommended effort should lead to powerplants that are cost competitive with gasoline-fueled engines, which might preclude a turbine design. The recommended engine should be designed around the most plentiful airline fuel although the ability to run on more than one type of fuel is desirable. Otherwise, the recommended research program possesses the objectives of NASA's proposed General Aviation Multifuel Engine (GAME) Program.

5. That NASA initiate the recommended programs as quickly as possible so that the results of the PET effort will be available within the next few years and that an intermittent combustion engine optimized for airline-type turbine fuel can be developed by the general aviation in industry for use in the early 1990's.

6. That NASA recognize the very long lead times associated with developing alternatives to fossil-based fuels and establish an exploratory program to examine the use of non-fossil fuel for general aviation.

FAA CERTIFICATION REQUIREMENTS FOR FUTURE FUELS, FUEL SYSTEMS, AND POWERPLANTS

Thomas C. Horeff
Federal Aviation Administration
Aircraft Engineering Division

As far as the FAA is concerned, the problem of fuel availability is not the only problem. Within the last two or three years, various proposals have been submitted to the FAA concerning the use of alternative fuels in general aviation aircraft. This morning, I would like to address the subject of certification requirements for alternative fuels for use in general aviation aircraft. Notice that the published title of my presentation has to do with future fuels. Trying to develop some comments with respect to future fuels, I found myself very inadequate to forecast what some of these future fuels might be. So I am going to address what are the current FAA procedures for approving fuels, along with a comment or two as to what might be done relative to assuring the safety of using these alternative fuels, whatever they may be.

Fuels used during engine and airplane type certification programs are approved by the FAA as part of the engine and airplane type design. The fuels are then listed on the type certificate data sheets for the engine and the airplane. The regulations pertaining to engine certification are contained in Part 33 of the Federal Aviation Regulations (FARs), and those with respect to the aircraft are contained in Part 23 of the Federal Aviation Regulations.

I think it is appropriate at this time to mention the reorganization process that is going on right now relative to both the engine and airplane certification programs. Previously, the regulations and policies pertinent to the showing of compliance to the rules were developed by the staff in the Washington Headquarters. Over the last several months, however, there's been a change in this approach and now the responsibility for developing the rules and policies has been transferred to lead FAA regions. With respect to engine certification, the lead region is the New England Region, headquartered near Boston, Massachusetts. With respect to general aviation airplanes, the lead FAA region is the Central Region, headquartered in Kansas City, Missouri.

Approval for the use of alternate fuels may be obtained by amending the existing type certificates. This is done when applications for approval for an alternate fuel are made by the engine and airplane manufacturers. When the application is made by someone other than the manufacturer, approval is handled by the issuance of a Supplemental Type Certificate, STC. In either case, the test programs that are required have to be approved and witnessed by the FAA. If a certain "future fuel" is used, and that particular future fuel happens to require "unique or novel" changes to the engine or the existing airplane fuel system, or both, special conditions will then have to be adopted to handle the particular unique or novel features.

Prior to conducting the certification tests, it is very desirable if the alternate fuel is covered by a specification that states the properties and limits by which uniform quality and composition of the fuel can be maintained, similar to the way the quality of current aviation gasolines are assured. In addition, the alternate fuel must be shown to be compatible with the airplane and engine materials in contact with the fuel and, depending upon the type of fuel, with any additives, lubricants or other approved fuels that are used in the engine and aircraft combination.

The engine test program, according to Part 33 of the FARs, must include calibration tests which establish the ratings and other limitations for the engine, a detonation test, and a 150-hour endurance test. At the completion of the 150-hour endurance test, a power check must be performed to assess any deterioration in power that may have occurred during the 150-hour program. In addition, the engine must be disassembled and inspected to make sure there is no evidence of abnormal wear, deposits, metal attack or other harmful effects that might have occurred during the test program.

Attention must also be paid, as far as the airplane certification is concerned, to the airplane's fuel system. The airplane fuel system, of course, must provide for a fuel flow at a rate and pressure established to assure proper engine operation. The test program must also include tests to simulate the most critical operating conditions; for example, using fuel at an initial temperature of 110°F to look for vapor lock, or possible unstable fuel pressure or fuel flow problems. Powerplant cooling tests with a particular alternate fuel is another example.

In summary, this is a very broad brush representation of what the requirements are for the current fuels and what the requirements would be in the future relative to the approval of alternate fuels.

AVIATION ENERGY AND THE FUTURE OF THE RECREATIONAL USE OF SPORT AND GENERAL AVIATION AIRCRAFT

Paul Poberezny and Harry Zeisloft
Experimental Aircraft Association

REMARKS OF MR. POBEREZNY

The Experimental Aircraft Association was formed almost thirty years ago as a creative association and not only for the purpose of trying to build aircraft solely for recreational purposes. It was and continues to be my philosophy that men and women who use their minds and hands can be very creative in aviation. The Experimental Aviation Association (EAA) started that way. But times have changed. What kind of aviation society do we live in? I think we are in a "yeah --- but" situation. My approach is, "Why can't we do it?"

We are thirty years too late in having a meeting such as this, and also in being concerned about energy--alternate energy and its effect on the future of aviation. I can remember eight or nine years ago, when I started to be concerned about energy, a lot of people did not share my beliefs. There was a lot of fuel back then, and arguments about auto and aviation fuel weren't much of a concern. But, as of today, history has shown that fuel is now of great concern--not only its cost, but its availability throughout the nation. If you want to start a new fixed base operation (FBO) in general aviation, just try to buy some aviation fuel for your storage tanks. Just try it. There's a real world out there! The real world is owning an airplane and living the life of an airplane owner everyday. It is a lot different than sitting in a conference room like this one and trying to plan the future.

Though some may disagree with me, there's a time to say certain things and a time not to. In my thirty years of asking people "Why do you own an airplane?", by far the majority reply, "for fun and sometimes transportation." But how we present this image depends a lot on to whom we are talking, and how we want to impress them. For government--be it local, state or federal--we can shape our future by saying that it is "all transportation." Nonsense! I own five airplanes, including some very expensive ones. Yet Harry Zeisloft and myself came here on Northwest Airlines because I know when to fly and when not to fly. Because of the extremely cold weather in Wisconsin, I only get about 15 "turns" out of my little energy packet (i.e., the battery) to get the engine started. Once that battery goes dead, I really have a problem.

At the present time there are some eleven thousand amateur-built aircraft certified in the United States in the experimental category. In addition, there are between eighteen and twenty thousand under various stages of construction. Do you know what a brand new 180 horsepower Lycoming engine costs? Around $10,000. And a lot of EAA types are buying them. Do you know what a biplane kit costs, complete with a 180 horse Lycoming? $35,000. Just one maker has about 300 kits backordered. I bet you didn't know that there were people out there willing to spend that much for a little homebuilt biplane. It certainly helps Lycoming. And it helps our other engine manufacturers, too. Many new businesses have been created as a result of our citizens

buying materials and building their own airplanes. But out of this, something even better is happening--self education. Within our country, people are developing a greater appreciation of craftsmanship and quality, and people who have an understanding of the manufacturers' problems in building and maintaining airplanes.

Much is going on in powerplant developments. In the coming "ultralight" movement, men and women who have always wanted to fly are about to have their chance. Here we have both the technology and the ability to make this possible, but all too often, we tie our hands with "yeah---but"; that is, we can't do it, or we don't have the specifications. So I suggest --- let's make one. Is there anyone here in this room today who can provide me with the specifications that created the basis for 100 no-lead avgas? How did this fuel come to be both loved and cursed by plane owners?

Six years ago we started a project called "Spirit of St. Louis." What we did was to build a replica of the Spirit of St. Louis in approximately 90 days. Our dream was to bring the spirit of aviation and what Mr. Lindbergh did in the "good ole days" (which by the way, caused many of you to become involved in aviation) to the American public. We completed this airplane and I flew the first test flight from the rear seat.

It was then that I came to have a great appreciation for all those accomplishments of Mr. Lindbergh. What a dog! This particular airplane was certified in the experimental category. (We operated the airplane, as we do all our test work, in the proper categories and observed the proper operating limitations. Then we flew in the designated flight test area. If you are leading an organization, you had better go by the rules and set an example). When it came time to ask for an amended operating limitation, I contacted our local FAA aviation inspector. American Oil Company had offered to provide <u>all</u> the autogas for the whole trip. They even offered to contribute $35,000 if they could have their logo on the side of our chase plane. Then we ran into "Yeah --- but." The FAA said you can't use car gas and fly around the United States; you've got to stay in the designated flight test areas. About that time, I had had enough of no-can-do attitude and I thought, well, I couldn't think of a finer agency to have stopped the Spirit. After I cooled down, I got together with FAA personnel assigned to the Great Lakes Region. I really felt sorry for those FAA engineering folk who yesterday didn't know anything about car gas, or even avgas, but today had to be experts. American Oil brought in several of their fuels and lubricant engineers. I brought in the manual we were using for our 7-cylinder, 220 horsepower Continental engine. We all sat down, and I asked, "How are we going to do it?" It was a very enlightening experience for me. No one there knew much about the aviation fuel area. One FAA fellow said that the fuel didn't have the right octane. I pulled out the old Continental manual and showed him that the engine had been certified on 63 octane. Well, the FAA then said, "We were going to have vapor lock problems." I asked, what do you want us to do? They replied, "You are going to have to heat-soak the fuel to at least 110^{o}F; then you are going to have to take off, climb as high as you can, and see if vapor lock occurs." Keep in mind--this is just 6 years ago!

Now, just how do you heat gasoline to 110^{o}? We ended up using water troughs that are used for cows. We got a bunch of heaters to heat up the water. Then we we put the gasoline in the troughs to heat it up. Next we got the engine cranked up and all warmed up. We had already put 100 octane fuel in one tank. Then using a ladder we filled the other empty tank with hot gasoline. Finally, we took off down the runway, climbed to 14,000 feet and--surprise--nothing happened! So, the FAA said, "Okay, you can go on the nationwide trip, but, this doesn't mean it is 'right'."

But it did set an example. Today, we must look to the future and try to make cheap energy available . . . whatever it takes. If it takes the installation of special pumps and wing tanks to get the fuel to the carburetor, why not? I just spent almost $7,000 on an AD note, just to keep flying my Cessna Twin. It appears to me that with this energy situation you have two choices: sit on the ground, or fly. And Lord knows, it is expensive enough as it is.

Now I will introduce Harry Zeisloft who will explain the test flight program that we've been involved in. This test program is intended to investigate the feasibility of using autogas in lieu of avgas. So far, we've flown three of our aircraft about 1,500 hours under controlled conditions, using a 180-horsepower Continental engine. Our current flight tests involve a Cessna C-150 powered by a Continental O-200 engine using American Oil Company no-lead autogas.

REMARKS OF MR. ZEISLOFT

Today I would like to give our opinion about what the future looks like for energy in the "sport aviation" field. First, we need a good working definition for "sport aviation." And I am happy to see that I am in a sympathetic crowd that doesn't think it is immoral or illegal or sinful to have fun. That's what sport aviation is all about; it is really fun flying. I define sport aviation as "aviation pursuits by individuals for personal satisfaction and enjoyment." Even if you own your own company and manage to fly in the left seat of your Lear jet, that to me is still sport flying. I understand this thoroughly because I spent a career in engineering with the primary objective of earning enough money so I could support an airplane.

The major technological threats to sport aviation, I think, are two-fold. The first is what we will be discussing this morning and that is fuel availability and fuel cost. The other major threat is the required "method of compliance" with the Federal Air Regulations. Now don't get me wrong--we don't see anything wrong at all with FAR 23 as a design tool, but we do see a lot of problems with the costs associated with the certification of new aircraft and engines. To those who say "boy, we're in the aerospace business--we are right at the needle point of technology," then I would have to ask you why a 1947 Bonanza is still a damn competitive airplane in today's market? So, along with stating our opinion and make some suggestions, I'd like to talk about our views as to some short-term technical programs.

First we need to develop fuel systems to handle the most readily available fuel--and I am <u>not</u> going to talk about automobile gas! I am going to talk about the most <u>readily available fuel</u>, whatever it is. Maybe in 1985 it will be Gasohol, or methanol, or ethanol. Maybe the only fuel available will be turbine fuel, because that is what the big users, the airlines, consume, thus making it in large supply. Second, we need to develop more realistic fuel specifications. The reason for this is to improve the economics of supply. We <u>need</u> an alternative fuel to replace Grade 80 avgas. We also need an alternate fuel to replace 100 octane. And when we talk about the economics of supply I want to also include within this thought the costs of the distribution system. Much of our problem is that the distribution system is tied right into the specialized fuel that we're presently calling aviation gasoline. Third, we need to develop basic data. This is where NASA is needed and where NASA can do a tremendously useful job for general aviation. We need basic <u>data</u> to provide the necessary design parameters for these new technology systems. Fourth, we need the FAA and other governmental agencies to cooperate in redefining the philosophy of compliance with the Federal Aviation

Regulation. Fifth, for long-term technical programs, we need to develop a basis for an orderly transition from avgas to some other more readily available fuel. To this end, we need to establish a data base for both a viable retrofit program for the existing fleet and for relief from overly conservative Federal Aviation Regulations as they pertain to fuel specifications.

I see our technological approches falling into either the piston engine or turbine engine category, using a readily available fuel. The reason for this is that with the way things are going, I don't think general aviation can afford to demand something "special."

Regarding which technologies require attention, certainly octane rating problems must rank high on the list. In order to check the rich rating of avgas, one must avail himself of one of only three or four engines in the entire country that can go through this rather complex process. This amounts to having a tool that nobody can apply. How can we find out whether a fuel is adequate or comparable to other fuels without being able to readily measure its octane characteristics. Further, we need an extensive material compatibility study. Not much new technology is needed here. But we do need to recognize that future fuels may be gasoline, alcohol, fuels with higher aromatics, or a mixture of these fuels. We also need engineering design studies that can define the vapor lock boundary conditions for fuel systems. I think most of us here today can sit down and say, "Well, I know what happens' I know what causes it. When you have an 'elbow' here or a reduction in size here, that's the place to look for vapor lock." But nobody has any real information to enable one to sit down and design a fuel system for fuel with given vapor characteristics and expect to be anywhere near a real end result. While there is nothing wrong with doing it empirically, it is just one of those things that would help get the answers in a more direct and less costly manner. Another area that needs technology's help is in engineering design parameters to replace the empirical approach to fuel and induction system icing. It is fun looking at all those big pictures of airplanes spraying out water and the airplane following it all covered with ice. I hate to think that another war is what we need to get going on these kinds of problems, but we all remember what happened in World War II and the tremendously detailed studies that went into developing efficient airscoops for piston engines. Additionally, NASA, please help us find a practical method for evaluating the influence of fuel additives on the safety aspects of power plant systems. If you don't, the FAA is going to tell us that we must run 1,000-hour tests on every gallon of gas with different additives that we expect to put in an airplane.

Changing subjects slightly, this is how we see the changing energy scenarios over the next several years. But let me tell you, ours is from the viewpoint of us "little people" who are struggling to keep one foot in an airplane cabin. This is what we have to say: In the near future, which I define as 1981 to 1990, we expect to see the total elimination of grade 80 avgas. Now, that certainly comes as no surprise to anybody--we're halfway there now. We also expect to see a flat demand for grade 100 octane low-lead and a somewhat increased demand for turbine fuel. Let me tell you the thinking that went into our analysis. In the newer airplanes, the trend is for greater ranges and higher altitude operations for the obvious benefits (i.e., for smooth transportation at altitudes with pressurized cabins). As a business tool, with the tax structure in our country, the out-of-pocket costs are not important. Therefore, I expect more and more turbine engines going into aircraft destined for the business fleet. I would expect to see more turboprops and, to a somewhat lesser degree, more turbojets. Consequently, I expect to see a continuing increase in the number and use of turbine engines in general aviation. On a mid-term basis, 80 octane is gone, and 100 octane is limited with its demand going down as turbine fuel demand goes up. So in the longer

term, we'll be at a place where general aviation single-engine airplanes cannot afford the distribution system nor the fuel itself. So--why don't we recognize this scenario now and do something about it!

If we talk about the longer term, from 1980 to 2010, I see the complete elimination of grade 100 avgas. This will force all existing piston powered airplanes to use the most readily available fuel for the piston fleet. Whether that is autogas, alcohol, or any strange combination we do not know of now, I cannot predict. Still on the long term, we see the replacement of the piston engine with the turbine engine in all newly manufactured airplanes. We see turbine engine fuel as the only fuel distributed solely for both air carrier and general aviation aircraft.

On an aside note, I wish to recognize that there has been a lot of work done on the revolutionary type new technology--piston engines. I think these new technology engines will be a minor factor in the future designs. This is because of the increasing demand for turbine engines in business aircraft and because there is high risk involved in the operational area due to the mechanical complexity and the potential reliability loss of these excessively complex new machines, especially when turbocharging and turbocompounding are used to get the needed high specific outputs. But I think more important than all the technical issues is the cost of original certification. I think when these new engine programs are presented to the board of directors of a Teledyne or an AVCO, or to any other potential engine manufacturer whose objective in business is to make money, they are going to look at the costs of certification and the potential market and say, "We cannot afford to make that big an investment; the risks are too high." So, those are the scenarios that we "little people" out here see.

Autogas and the EAA Flight Test Program. What kind of solutions are there to the aviation energy problem as seen by us "little airplane people?" As I stated earlier, we see a doing away with the low octane number avgas. We think a far healthier replacement, or substitute, is automobile gas in most of these lower compression engines, rather than 100 octane low-lead. By the year 1990, we think that the then current technology engines and fuel systems will be designed to use the most "readily available" fuels, whether that is automotive gasoline or Gasohol. And we think that by the year 2000, single-engine aircraft with up to four seats will still use current technology engines but with evolutionary improvements, and will be operating on "readily available" fuels. In the possible but uncertain category, I think even 100 octane avgas can be replaced by premium unleaded autogas. To accomplish this, it may be necessary to enhance the octane rating of the autogas. However, I don't see why we cannot also look at the possibility of derating these engines and relieving some of their maximum operating envelope conditions. You may retort by saying that we have worked long and hard to get our engine efficiencies up to where they are today. But my response to you is, "Are we going to fly a lower efficiency plane or not fly at all?" I really don't think there is a very healthy future in store for aviation gasoline. In the 1990-2000 period, we think that advanced technology piston engines using turbine fuels are a possibility, but I would rate their development as highly uncertain. By the year 2000, it is our belief that all general aviation multi-engined aircraft would use turbine engines, replacing the older piston-engined business fleet. In the very near future, like the next three to four years, it is unlikely that we can have fuel systems retrofits and engine derating programs that would allow the use of autogas in all aircraft regardless of their original octane requirements. It seems to me that there is just too much technical data to be obtained and analyzed and to act upon than we can handle in that time period.

I will now describe what we at EAA have been working on in the autogas area. Our objective was to obtain actual test data on the use of unleaded autogas in place of grade 80, and having this data, we would expect to be able to modify an aircraft's powerplant system and to then obtain data on the modification. Ideally, what we want to do is justify an STC for that modification.

Our test aircraft is a Cessna 150 with a Continental O-200 engine certified to run on grade 80 avgas. We have installed an auxiliary backup fuel tank to hold avgas when we are exploring the operational limiting aspects of using autogas. Our instrumentation includes thermocouples, a digital readout, and a Fluke stripchart recorder. Readings from RPM and altitude measuring transducers are printed out on our recorder. Also, we are recording exhaust gas temperature (EGT) readings as well as the head temperature on all four cylinders. We also are recording the engine compartment temperature, the carburetor bowl temperature, the temperature in the intake manifold spider, the fuel temperature in each tank, the cabin ambient temperature, and the outside air temperature. In general, all operations have been satisfactory. To date, we have been unable to identify any characteristics of the test fuel which would affect the air worthiness of the engine. So far, our extreme operating conditions occurred on an 84°F ambient day, with an initial fuel temperature in the tank of 135°F. That ought to satisfy that 110°F requirement! During these tests, the carburetor bowl temperature was 117°F. After a harried consultation, we convinced our brave test pilot to go ahead and try it. And we did make the flight. During this particular test flight we ran the engine at full power at 1,000 feet, until the cylinder head temperature stabilized, followed by a minimum airspeed, maximum rate of climb. Unfortunately we had to terminate this test at 5,000 feet because of cloud cover.

At present we are trying to decide, for the purposes of data recording, what interval of time is needed on each test. When we are doing a transient condition we take data at 30-second intervals until we get through transitional flight conditions. Then we record data at 5-minute or even 10-minute intervals. As you can imagine, we have a tremendous amount of data. With our relatively small staff, this is presenting us with quite a problem.

What I have just given you is a quick summary of where we stand in this program. So far, we have not confirmed any theories yet. Summarizing our data, we have completed 198 hours of flight testing using this airplane. We made 567 takeoffs and landings. We have run 17 hours at maximum power, and 152 hours at cruise power. We have used 913 gallons of autogas and 17 gallons of avgas. We have had four oil changes. We are doing a standard analysis on oil and we haven't seen anything particularly unusual.

INDUSTRY'S ASSESSMENT OF THE NUMBER OF AIRPLANES IN THE GENERAL AVIATION FLEET, ALONG WITH THEIR HOURS FLOWN AND FUEL CONSUMPTION DATA, POWERED BY WHAT TYPE OF ENGINES, WHEN AND FOR WHAT REASONS, THROUGH THE YEAR 2000

Thomas J. Smith
Mooney Aircraft

My presentation is on behalf of GAMA--the General Aviation Manufacturers Association--a group of some 38 members including airframe, engine and avionics manufacturers.

The purpose is to look at the future of general aviation, its fuels, and the piston powered fleet of aircraft up to the year 2000, and beyond.

In many ways, this presentation parallels our industry's recommendations made to NASA in 1979 in a paper entitled "General Aviation and Energy--R & D Needs for the 1980's."

The time frame considered in 10-year increments:

*Near-Term: 1981-1990
*Mid-Term: 1991-2000
*Far-Term: 2001 and beyond

My approach was to develop a meaningful framework from which to lead this group through this very complex subject. Our focal point is the marketplace. In some ways, it is like a soft rubber ball--you can squeeze it; it "squeezes" back; it reacts under the pressure of various forces.

There are forces which are always shaping and molding our market, and as management we must understand these forces--and stay ahead of them. Our very corporate survival depends upon doing this--constantly. I call these forces "dynamic forces in flux."

Collectively, as an industry, we face a set of variables which are these "dynamic forces in flux." Let's look at several of the more important ones that are of concern to us here today. These are summarized in Figure 1.

Let us first start with "social and cultural considerations," that is, the needs and wants of our customers. If society doesn't want our product, and if advertising can't persuade them to change their minds, it's a waste of time for us even to consider it. The customer has the final say as to what he wants, and we in industry must, ultimately, be responsive to his needs. By cultural considerations I mean that what may be good for us as Americans might not be acceptable--or saleable--in other parts of the world.

Before we go further, let me address product liability. In recent years, product liability judgments have gone wild. While I'm certainly not in favor of irresponsible

management, and support punishment within our legal system for trespasses in this area, we must all recognize that product liability considerations have limited us in instituting innovation. In many cases this lack of innovation runs against increasing productivity, and in our case this morning, in attempting to develop unique and beneficial solutions to significantly improve our energy efficiency. I also might add that these product liability considerations, coupled with sound technical facts, will be a major restriction to the use of automotive gas in aviation.

Next comes our needs as businessmen. We're the manufacturers whose business is making and selling airplanes. We too have certain needs and considerations such as: our investment in our existing capital equipment and production base, the problems of capital formation, including getting reasonably priced financing, and ultimately, the rate-of-return (or ROI) to our shareholders, the owners of the corporation. In our free enterprise system, we must make a profit to stay in business, to grow and to prosper.

Another limiting constraint, but one that we accept more than not, is the need for environmental responsibility. Airplanes need to be quiet. We in general aviation need to be good neighbors, and for us as manufacturers, we need to develop quiet and non-noise polluting engines. But as engineers you know that design often includes compromise. Just how much is too much? To meet new noise criteria, you usually sacrifice something, and that something is oftentimes efficiency.

Then there are the international trade and competition issues. The aviation business has historically been one of high technology, especially in the large transport category airplane group. But even the smaller, general aviation planes are high technology. America is unique in that our planes have been traditionally a "plus" on the balance of payments ledger. We would like to continue this trend. Exports accounted for 30% of our shipments in 1980. We in industry must continue to address the marketplace as truly an international one, and must meet our foreign competition with the best products America can produce.

Concerning the political and regulatory, including FAA certification and recertification requirements, we all live in a world of law and order and of political constraints. This includes those who build and those who fly airplanes. As I begin to focus on the issue of this paper--energy--which I will do in a minute, I urge you to think about our previous speakers' presentation, that is, the FAA's presentation on certification. We in industry will need to work with FAA in certifying the new hardware that may come as a result of our recommendations here today, as well as to recertify existing airplanes with this new technology when and if it proves to be both successful and feasible. Without timely FAA regulatory approval, we incur yet another restraint, or constraint in the marketplace.

Next, I would like to say a few words about the role of general aviation in the transportation of goods and services. Harry Combs, in an editorial in Pro-Pilot Magazine in September of 1979, wrote an article on time, productivity, and the whole concept of time and space. One of his points--California, from Cleveland, is no longer 1700 miles or so away, it is only 4 hours distant--time is the dimension of the 20th century and certainly of the 21st century. And until we can develop machines that convert matter into electrical energy, and then to transport that energy over vast distances at the speed of light, we must be content with our "earthly carriages," with the airplane, especially the jet, as being the fastest means available to transport men and materials. To this end, general aviation is part of our nation's and the world's transportation system. True, we compete with other modes of travel--auto, rail,

bus--and compete also among ourselves (the small piston end of the market competing with the faster planes like the Learjet, Citation--and the Mooney 231 for that matter!).

The point is that to meet the needs and wants of the various segments of the market, industry has developed a "fleet mix" of airplanes, from the light, single-engine, general aviation piston-powered aircraft to the commercial transports and even the Concorde. We perceive this need for a "fleet mix" to continue indefinitely.

Let us go on to the reason why we're here today. In 1973, the world awoke to the realization that energy was no longer a "free good," as the economists would say, and that it had been for years, underpriced. Also, in 1973, we awoke to the realization that cheap energy could never again be taken for granted--and that it may not always be available, both domestically and internationally. For the rest of our lifetimes, "times have changed." We are still in this period of realization and readjustment, but the key point is that without readily available cheap energy, airplanes as we know them today have limited utility. Without energy, airplanes are worthless in getting people from point A to point B.

Since 1960, with the introduction of the commercial jet, avgas as a product has been in a declining phase of its product life cycle (Figure 2). In the mid 1970's, it started to experience an upturn in demand, but compared to yesterday, things will never again be the same. In a later section, I'll address how industry sees the avgas supply and demand picture through the year 2000.

Before I leave this subject, however, I might add that with the decline in the volume of avgas production came a major change in the way avgas was distributed. Until then, pipelines sufficed as an efficient and cheap means of distribution. But no longer. Truck transports are used today (except for a few pipelines), but truck shipment is expensive and limited in both size and utility. And at the FBO level, with low turnover volume, costs are inordinately high. Something has to give, and that's price. The points shown on the map in Figure 3 represent the current avgas production locations in the U.S.

The price of avgas and jet fuel has gone up and will continue to do so. In 1970, avgas cost 40 cents per gallon. Figure 4 shows some recent prices. Retail price, of course, reflects the cost of crude, processing, distribution, taxes, and profit. All indications point to the fact that prices will continue to rise. And, as classical economics tells us, as real prices rise, people will opt to use less, or will switch to other, cheaper sources of energy. Another point to consider is that some of the ingredients in avgas are also used to build the octane pool for other petroleum products, notably premium no-lead mogas. The demand on the octane pool is increasing, and so, its price will also likely be bid up. What's the bottom line? We anticipate that discretionary flying--for personal use, instructional and proficiency flying, as examples--will suffer because pilots will no longer be able to pay the price. Pilots with a marginal interest in flying will simply give it up. The impact on business flying, which pays for fuel with "after tax dollars" will be much less but here, too, there will be an effect.

So, what can we, the "moguls" in the general aviation industry do, to help resolve the problem? Well, conveniently, the last item that I chose to talk about that impacts the marketplace is "technological innovation." This is what America is all about! Cars, trains, airplanes--the first man to the moon--were all "built-in-USA." And so today we again face a challenge, that is, how to resolve this apparent and projected

"discontinuity" in our energy future. The rest of my presentation will focus on what we as manufacturers foresee and recommend be done in the technical area to maintain and improve the climate for the continued growth of general aviation.

In summary, Figure 1 shows how we in the industry perceive the marketplace. We see major "dynamic forces in flux," each shaping and changing the environment in which we conduct our business and the environment in which we all live and work. Our marketing radars, are telling us there is need to change. And because of the normal "delays" in both R & D and engineering development, in production engineering tests, in certification, and in market introduction and acceptance, the time is now to start harnessing technological innovations, as well as to develop other adjustive strategies to keep the other "dynamic forces" at bay until we have this new technology in hand.

What's our solution, you ask? First, avgas is in a second phase of its product life cycle. Second, national and local distribution of avgas will remain difficult and complex issues. The fact is that the logistics of trying to move small quantities of avgas to far-flung reaches of our country, and the world for that matter, is a most difficult task. Third, the price of avgas will continue to increase in terms of real dollars. If we realize that avgas is a premium fuel and also, one that commands a premium price because of its low volume and the cost of quality control and of distribution, then one can logically expect its price will continue to increase over the next ten to twenty years. Whether its price will increase in disproportionate terms in comparison with other petroleum products is a matter for further discussion and analysis.

So, the key question remains: Will sufficient quantities of avgas (or a suitable substitute) always be available in future years to meet demand?

Our answer is "yes"--as long as there is sufficient demand for the product; and as long as it remains a profitable item, someone will continue to produce and distribute it.

However, our concern is three-fold. Will the price be reasonable? Will there be sufficient fuel available? And will the amount that is available be a constraint on industry growth? Can improved technology in the 1980's be used to enhance general aviation and insure that price and availability will not be constraints on growth? This is what we think . . .

We, as an industry, have reviewed both the existing fuel technology base as well as possible new engine technology for the smaller, lighter end of the general aviation market. We have concluded that any future fuel for general aviation must meet certain criterion. They are:

- be available;
- be relatively inexpensive;
- have an in-place, simple distribution system;
- have a high BTU content per gallon or pound;
- be easily handled;
- be safe;
- have a technical specification (or standard) that assures high quality control.

To this end, we have prepared Figure 5. It compares the properties of various fuels with the exception of electric fuel cell technology. The key findings here are that avgas, unleaded premium autogas, and the various jet fuels combined show the greatest promise in terms of BTU's per gallon. When you consider the "tankage" needed to contain the same amount of BTU energy for these different fuels, you once again become locked into these same fuels, plus liquid propane.

I might add, however, that electrochemical fuel cell technology is not included in this analysis. The reason for this is that it was difficult if not impossible, given the organizational structure of this chart, to compare "apples with apples," i.e., an electrochemical process with fuels used in Carnot type heat-cycle engines. Further research and analysis is needed to determine the potential--and limitations--of fuel cell technology for use in future general aviation aircraft.

I might add that, as an aside, the reason why fuel and tankage "penalty" is important for conventional liquid fuels is that it relates to the BTU content of the fuel. For heat liberating engines, aircraft range is proportional to the heating value of the fuel, as Figure 6 shows. More BTU's per pound of fuel means greater range. Notwithstanding, if your fuel BTU value is less, you can consume more fuel, that is, increase your flow rate, or derate the engine. Both of these alternatives affect range and performance.

And, of course, the octane rating of the various fuels is important for gasoline piston-powered engines. In a gas turbine or stratified charge engine, octane value is not an important consideration. So, as far as conventional piston engines go, the higher the octane the smaller the engine, as Figure 7 shows.

Now then, returning to my original "criteria" matrix, and filling in the blanks, we arrive at the following conclusions in Figure 8: the jet fuel family seems to be the best "across-the-board" candidate fuel for general aviation, given our existing knowledge base. Specifically, the fuel is available today, and because it is so simple to produce, the chances of it being available in the future are also good.

I might point out, in terms of synfuels, that jet fuel from coal and oil shale promises low cost and, as such, is an additional plus for the selection of jet fuel as being the best and most readily available liquid fuel for general aviation in the future. This is shown in Figure 9 which summarizes the energy required to produce various types of synfuels.

Returning to Figure 8, and still on "availability," jet fuel in comparison with both avgas and autogas needs no octane additives. Also, since production is simpler, jet fuel should remain a relatively cheap fuel to produce. Jet fuel also has an in-place and simple distribution system. It is already available at many airports and is the fuel used by many businesses and almost all larger transport category aircraft today. Jet fuel has a high BTU content and its handling characteristics are well known. Finally, jet fuel is a quality product and is governed by a strict technical standard that assures quality control--ASTM specification D-1655. It is for these reasons that the general aviation manufacturers are recommending that the engine of the future, whatever design selected, be designed to run on jet fuel or some derivative thereof.

So, in summary, what we see is the need for a new engine compatible with jet fuel--a reliable, safe engine comparable in horsepower with today's engines, with a lower specific fuel consumption, designed for use in the smaller aircraft of the general aviation fleet.

And what type of new engine can best do this job? Where should we place our bets? Well, as we see it, there are several choices. A greatly improved stratified charge engine, either piston or rotary, seems like it could do the job. Also, a small ultra-lightweight, low horsepower gas turbine engine could also perform well. The turbine offers certain other advantages that make it attractive such as low vibration and cabin noise; also, its bleed-air could provide both cabin heat and pressurization.

From a life-cycle cost point of view, it is generally agreed that the initial costs of any of these new engines will be greater than the cost of conventional piston engines of today and, therefore, technology should be aimed at longer life and lower fuel consumption to offset these higher costs. Facts seem to make us look closer at the stratified charge engine, or some configuration of it, as having the best chances for development and eventual production within the next ten years. Also of note is the fact that our total production base of existing piston powered gasoline engines can be applied to the production of these new stratified charge engines. Consequently . . .

"What if" . . . this new lightweight, reliable, safe engine, with horsepower comparable with today's engines, and with a low SFC, can be developed, and placed into production by the late 1980's in time for production aircraft to start reaching the marketplace by 1990. If so, Figure 10 shows what our fleet forecast might look like.

Based on very conservative estimates, this figure shows the impact that such engines might have on overall fleet composition between 1990 to the year 2000. We envision that the first engines delivered would be of a relatively large displacement and would go on multi-engine aircraft. After an initial "teething period," the engine technology would eventually gain wider acceptance and would begin to impact the single engine market by the mid to late 1990's, but at the same time, avgas powered aircraft (using existing engine technology) would still be produced, thereby also increasing the number of avgas powered piston engine aircraft in the fleet. However, because of the gradual introduction of these new technology engines, the composition of the U.S. general aviation fleet from 1981 through the year 2000 would undergo some changes, as Figure 11 shows.

Figure 12 shows our forecast of flying hours for the personal/discretionary sector of the general aviation fleet. As you may know, business flying today accounts for 75% of all general aviation activity, in terms of total hours flown. In this analysis, we have assumed that all other variables such as economic (which includes both real and relative prices), social, political, legal and all those other "dynamic forces in flux," remain constant during the period of analysis. We have also assumed that personal flying will be done primarily in the types of airplanes we make today.

Figure 13 shows the number of hours of business flying forecasted for the next 20 years, and our assessment of the "mix" between avgas powered and jet fuel (including non-turbine) powered flying. The key thing to note is that this new engine technology will affect business flying earlier and to a larger extent than the discretionary/personal flying sector. This is so because the first engines to come off the production line would be of larger displacement and would be for use on the larger corporate sized aircraft first--such as an airplane in the Cessna 421 class--and then would be installed on the high performance and payload end of the "singles" market. In 1980, this "high end" of the singles market was virtually all sold for business purposes. Whether future training planes would ever use this new engine is a matter of debate, and is open for later discussion. I might also add that, as in reality, there will be some swings--"ups" and "downs"--in this forecast, caused by both recessions and upturns in

our economy. Last year, for example, avgas sales were off some 10 percent due to a dropoff in general aviation activity.

Finally, Figure 14 shows our forecast of the amount of jet fuel and avgas used by both sectors, now and through the year 2000.

Avgas demand should increase at the rate of about 3 to 4 percent per year through 1990. Second, after that date, there will be a decline in the rate of increase of avgas. By the mid 1990's, the overall demand for avgas will start to decrease. Third, given our free economic system, a system called capitalism, we believe the marketplace will continue to provide avgas--or an acceptable substitute--for these avgas powered aircraft as long as there is sufficient demand. Also, recognize that even with the introduction of this type engine, and even after several models equipped with this engine start coming off the production line, aviation gasoline powered engines will still be in production, probably for use as trainers or in aircraft designed for other specialized applications.

Next, we recognize, and want you also to recognize, that the switchover to these new type engines will accelerate the decline in the value of existing avgas powered planes in the general aviation fleet, unless these new engines can be retrofitted into the older, existing aircraft already in the fleet. Our analysis indicates that this is feasible, especially if we develop these new engines from the outset with this in mind. I might add that FAA's role here is one of being in partnership with us and that certification and recertification procedures must be thought out well in advance and then implemented in a timely manner to make this retrofit scheme both feasible and cost effective.

Some of you might wonder why we as manufacturers see a need to perpetuate the life of these older airplanes when their demise could mean whole new markets for us. The answer is simple; the "value" of any airplane today is partially, if not entirely, dependent upon its "used" value at the time of resale.

Figure 15 forecasts avgas consumption through the year 2000 . . . That's our forecast of how we see things if the industry, in conjunction with government--and that means both NASA and the FAA--starts today with the development of a new generation engine, one that would burn jet fuel as its number one choice. But this still leaves us with one remaining and a most important issue. That's how to address the "nagging" problem of those avgas powered piston engine airplanes that would remain in the fleet. Our assessment and position on this subject is summarized in Figure 16.

First, we believe that the demand for avgas will continue strong and unabated until some time after the introduction of this new type of engine. If the used airplane market deteriorates, then the "new purchase-resale" chain of events will fall apart. Our dealer network, our distributors, and our consumers will lose. And as they lose confidence in the viability and in the "immortality" of our products, then we too lose. Consequently, we as manufacturers must do everything we can to help maintain the value of the used airplane fleet. For in the end it serves our purposes too.

In conclusion then, Figure 17 shows what we the manufacturers see. First, in the next ten years no significant change in the composition of fuel usage of the general aviation fleet is contemplated. Second, if a major, well-thought-out, dedicated R & D effort is started now, we expect to see airplanes powered with new generation engines begin to enter the fleet by 1990. We see a jet fuel powered new technology engine, (such as a stratified charge or lightweight gas turbine engine) as being the least risk and

best hope of the future. This new type engine, which would consume jet fuel as its primary fuel, appears to be the most economical solution to meet the needs of the lighter end of the general aviation fleet. And finally, and perhaps most importantly, this new engine has the commitment by industry for its production. If it is developed and proves feasible-- technically, operationally, and, of course, economically--then it will be used.

THE MARKETPLACE
SOCIAL/CULTURAL CUSTOMERS NEEDS AND WANTS
PRODUCT LIABILITY
PRODUCTION BASE, CAPITAL FORMATION, & RATE-OF-RETURN (ROI)
ENVIRONMENTAL CONSIDERATIONS, e.g. NOISE & LAND USE PLANNING
INTERNATIONAL TRADE AND COMPETITION ISSUES
POLITICAL-REGULATORY, INCLUDING
FAA CERTIFICATION & RECERTIFICATION REQUIREMENTS
COMPETITION FROM OTHER TRANSPORTATION MODES
NEW TECHNOLOGY
AVGAS AVAILABILITY AND PRICING DOMESTIC AND INTERNATIONAL

Figure 1.

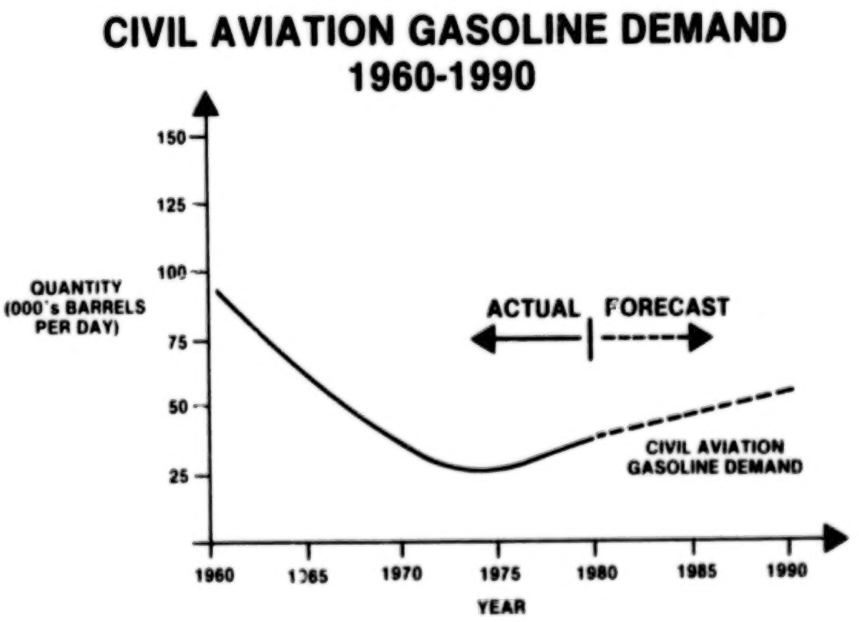

Figure 2.

U.S. AVGAS PRODUCTION FACILITIES 1981

Figure 3.

U.S. RETAIL "PUMP" PRICES OF AVGAS AND JET FUEL, AVERAGE, JANUARY-DECEMBER, 1980

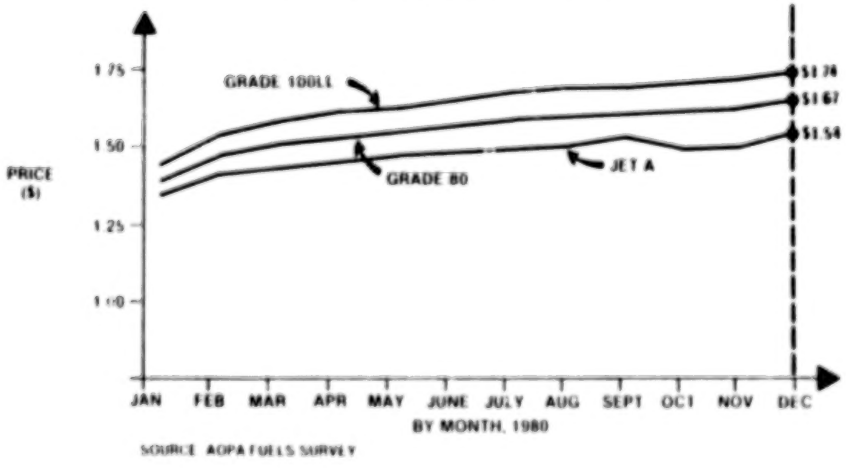

Figure 4.

COMPARISON OF VARIOUS FUELS

TYPE FUEL	CHEMICAL COMPOSITION	STORAGE PRESSURE (psig)	STORAGE TEMPERATURE (°F)	ENERGY DENSITY (Btu/gal)	AMOUNT EQUIVALENT TO 60 GALLONS BTU VALUE OF AVGAS		MOTOR OCTANE (CETANE) (Minimum)
					VOLUME (gals.)	WEIGHT OF FUEL + TANKAGE (lbs.)	
100LL AVGAS	C_4-C_{10}	0	60	109,512	60.00	381.0	100
UNLEADED PREMIUM	C_4-C_{10}	0	60	111,809	58.77	374.4	92
METHANE GAS	CH_4	2,000	60	20,376	322.50	841.2	105
LIQUID PROPANE	C_3H_8	100	60	84,605	77.66	390.1	97
METHANOL	CH_3OH	0	60	57,411	114.45	789.9	92
ETHANOL	C_2H_5OH	0	60	76,597	85.78	598.7	89
LIQUID HYDROGEN	H_2	0	-423	30,751	213.68	629.0	–
HYDROGEN GAS	H_2	2,000	60	4,633	1,418.24	1,040.0	–
METAL HYDRIDE HYDROGEN	Mg_2Ni-H_x	0	60	64,163	102.41	1,763.0	–
JET A (KEROJET)	C_{10}-C_{15}	0	60	124,200	52.90	387.1	40
JP-4 (NAPHTHA BASE)	C_6-C_{14}	0	60	118,864	55.28	387.1	–
JP-5	C_{10}-C_{15}	0	60	124,806	52.65	387.1	40
JP-6		0	60	125,120	52.52	387.1	–
DIESEL FUEL 1-D	C_{10}-C_{26}	0	60	141,000	46.60	378.1	40
DIESOLINE	C_5-C_{26}	0	60	130,000	50.54	383.8	–

Figure 5.

AIRCRAFT RANGE IS PROPORTIONAL TO THE HEATING VALUE OF THE FUEL

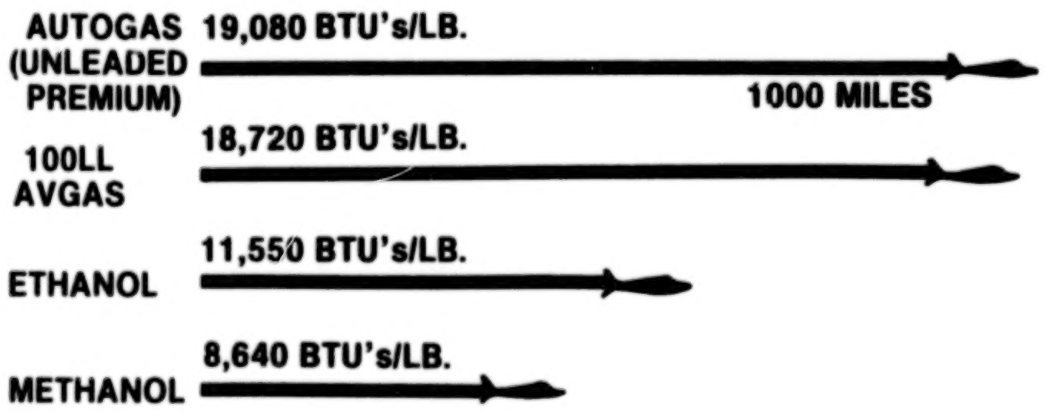

Figure 6.

FOR GASOLINE POWERED PISTON ENGINE AIRCRAFT — THE HIGHER THE OCTANE, THE SMALLER THE ENGINE

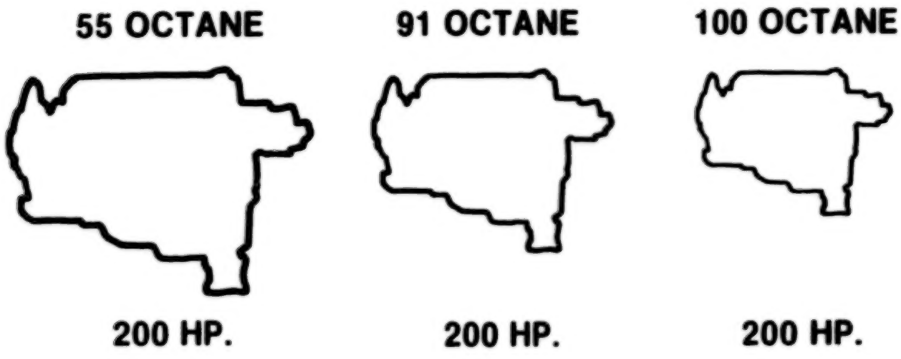

Figure 7.

AVIATION FUELS SELECTION MATRIX

	AVGAS	AUTOGAS	LIQUID PROPANE	JET FUEL	DIESEL
AVAILABILITY	YES	YES	YES	YES	YES
RELATIVELY INEXPENSIVE	YES	YES	YES	YES	YES
INPLACE, SIMPLE, AIRPORT DISTRIBUTION SYSTEM	YES	NO	NO	YES	NO
HIGH BTU CONTENT	YES	YES	YES	YES	YES
EASILY HANDLED	YES	YES	NO	YES	YES
SAFE (VOLATILITY)	SO-SO	POOR	POOR	GOOD	GOOD
TECHNICAL STANDARD WHICH ASSURES HIGH Q.C.	YES	NO	NO	YES	NO

Figure 8.

ENERGY REQUIRED TO PRODUCE VARIOUS TYPES OF SYNFUELS

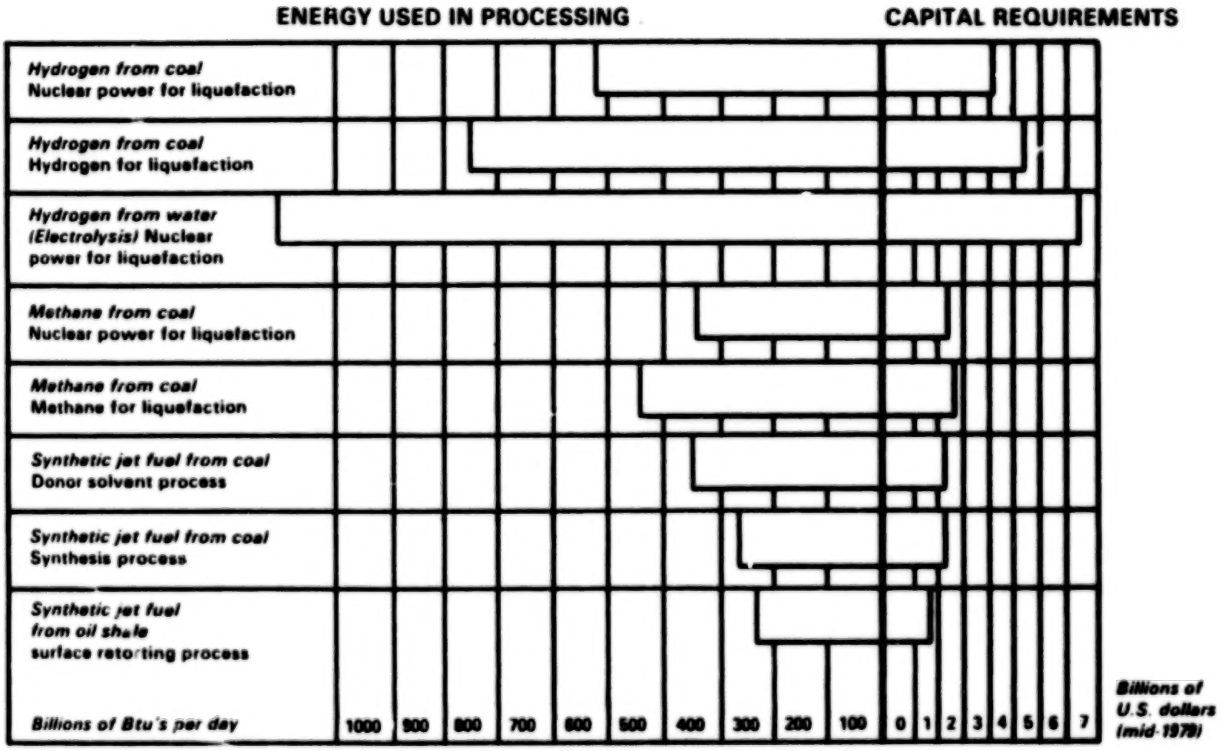

Figure 9.

ESTIMATE OF
U.S. GENERAL AVIATION PRODUCTION, 1980-2000
(ASSUMING DELIVERY OF NEW ENGINE EQUIPPED AIRCRAFT BEGINS JANUARY, 1990)

YEAR	S.E.-AVGAS POWERED	S.E.-JET FUEL POWERED (NEW-ENGINE)	M.E.-AVGAS POWERED	M.E.-JET FUEL POWERED (NEW-ENGINE)	TURBOPROP	TURBOJET/ TURBOFAN
1980(ACTUAL)	8283	—	2116	—	795	326
1981	8340	—	2000	—	910	370
1985	8500	—	2200	—	1000	400
1990	10,000	—	2500	—	1200	450
1991	12,000	200	2500	400	1250	475
1992	13,500	100	2600	200	1300	500
1993	14,000	500	2500	500	1350	550
1994	14,500	1100	2450	700	1375	600
1995	15,000	1500	2400	1000	1425	625
1996	15,000	1900	2350	1300	1500	650
1997	14,500	2500	2300	1500	1550	675
1998	14,000	3100	2250	1700	1600	700
1999	12,000	3500	2200	2000	1650	725
2000	11,000	3900	2150	2300	1700	750

Figure 10.

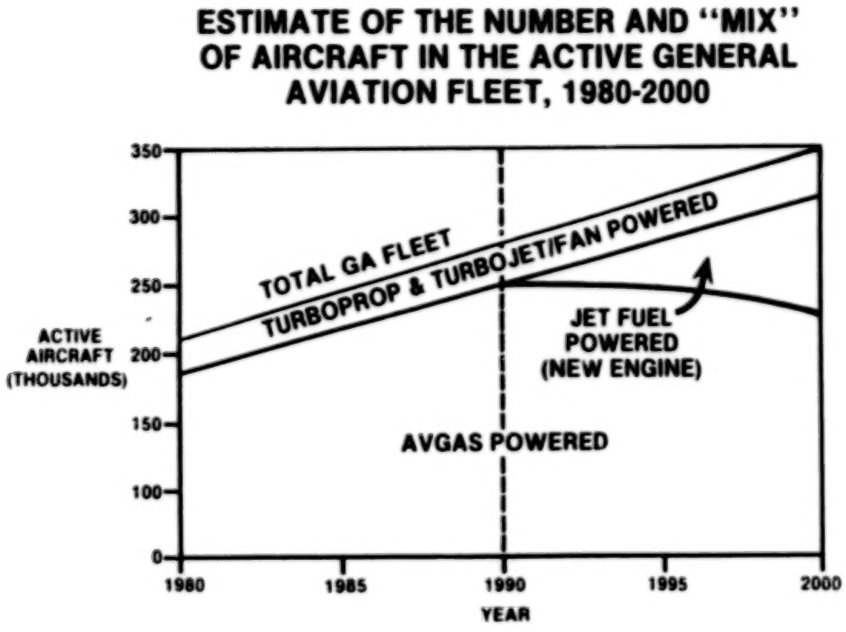

Figure 11.

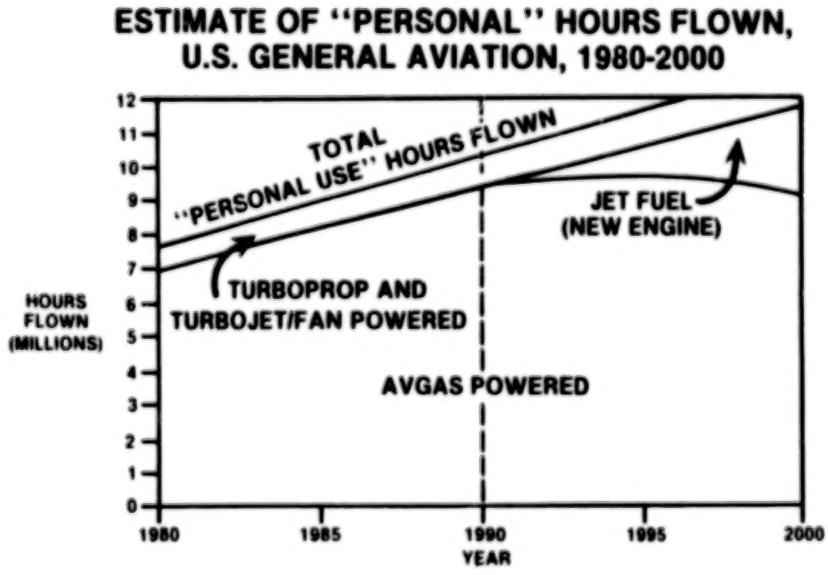

Figure 12.

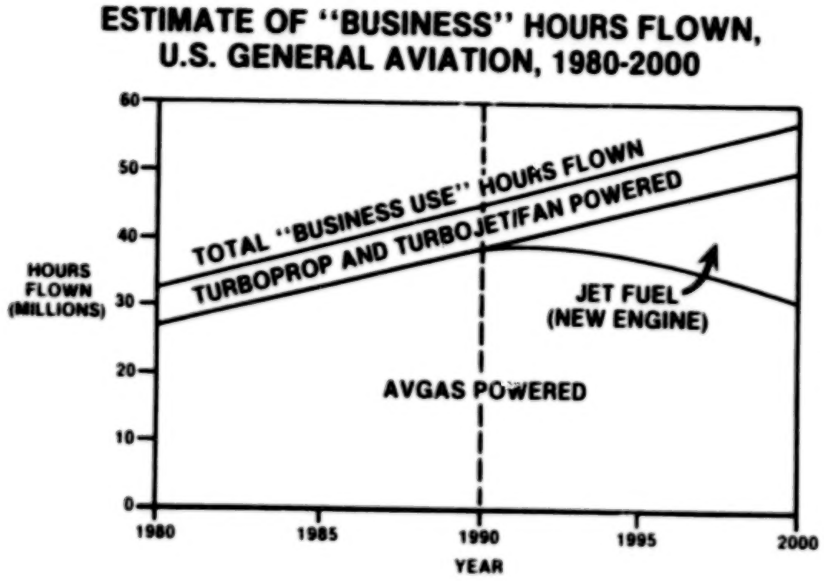

Figure 13.

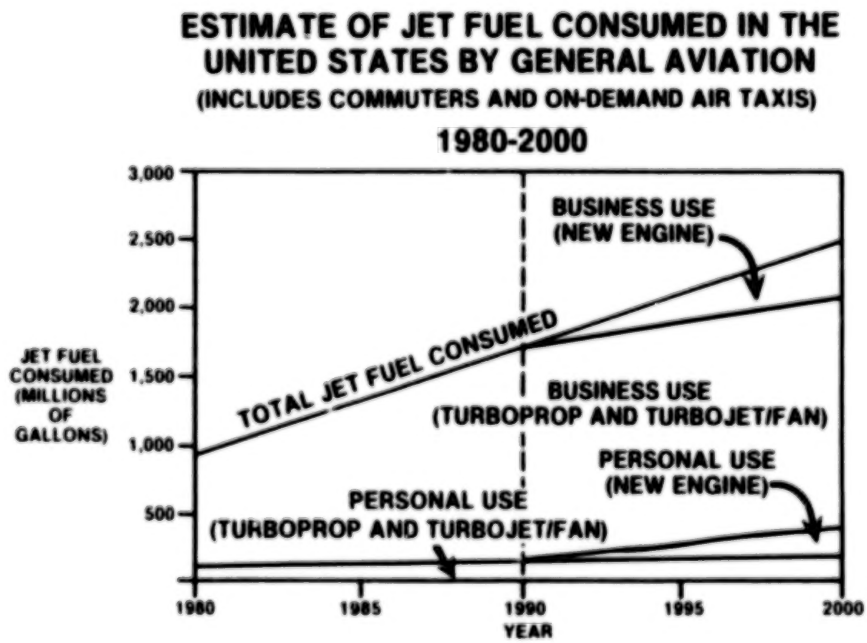

Figure 14.

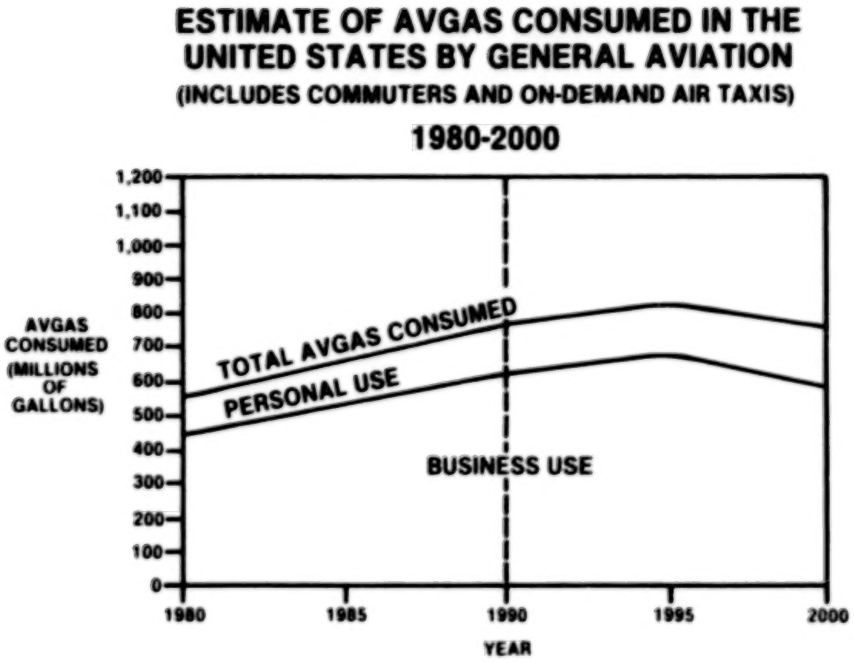

Figure 15.

INDUSTRY ASSESSMENT:

- DEMAND FOR AVGAS WILL REMAIN STRONG THROUGH THE 1990's.
- FOLLOWED BY A DWINDLING RATE OF INCREASE FOR AVGAS AFTER INTRODUCTION OF THE PROPOSED NEW TECHNOLOGY ENGINE.
- FREE MARKET WILL PROVIDE AVGAS (OR AN ACCEPTABLE SUBSTITUTE) AS LONG AS THERE IS SUFFICIENT DEMAND.
- RETROFIT OF NEW TECHNOLOGY ENGINES THAT USE JET FUEL IS FEASIBLE.

Figure 16.

CONCLUSIONS:

- NO SIGNIFICANT CHANGE EXPECTED IN THE COMPOSITION OF THE G.A. FLEET OR THE TYPES OF FUELS USED IN GENERAL AVIATION IN THE NEAR-TERM.
- IF R & D IS INITIATED NOW, NEW AIRCRAFT, POWERED BY NEW TECHNOLOGY ENGINES, CAN BE INTRODUCED BY THE MID-TERM.
- A JET FUEL-POWERED NEW TECHNOLOGY ENGINE (SUCH AS A STRATIFIED CHARGE OR LIGHTWEIGHT, LOW HORSEPOWER GAS TURBINE) OFFERS:
  - THE LEAST RISK/BEST HOPE FOR THE FUTURE;
  - THE MOST ECONOMICAL SOLUTION FOR THE LOWER END OF THE G.A. MARKET;
  - A COMMITMENT FROM INDUSTRY FOR PRODUCTION, ASSUMING THE TECHNOLOGY PROVES TECHNICALLY, OPERATIONALLY AND ECONOMICALLY FEASIBLE.

Figure 17.

PANEL DISCUSSION

MULTI-FUEL CAPABILITY FOR GENERAL AVIATION AIRCRAFT

Thomas Smith, Moderator

Introduction by Tom Smith/Mooney: This panel has no formalized agenda. Our entire objective is to try to surface as many different ideas and opinions from this august group as possible relative to the subject of "Multi-fuel Capability for General Aviation Aircraft." We do not have sufficient time to get into any in-depth analysis. Please direct your comments to the pitfalls, advantages, liabilities, and realities of how you perceive the need for multi-fuel capability for general aviation. Let me start the discussion by asking, "What do you think about multi-fuel capability for our general aviation airplanes?"

Les Waters/Teledyne: The term multi-fuel capability is misleading. It is like motherhood; everybody wants it, but are they willing to pay the price? What we know today is that any engine having multi-fuel capacity involves many compromises. These compromises dictate that adequate performance must be attained with the worst fuel and the consequences endured with the best fuel. Therefore, we must seriously consider if there is a need for multi-fuel capability given these inherent compromises.

Al Hundere/Alcor: There is a very definite need for multi-fuel engines. In fact, we have them now. If you land somewhere and cannot get the fuel specified for the aircraft, you have to use whatever is available. I encountered that with my Cessna 340 a little over a year ago. I was coming back from Brazil and landed at Grand Caymon Island. They announced to me after my landing that I'd have to wait 30 days to get any 100 octane fuel. I asked them what they suggest I do. They said to find an airplane coming in, such as a DC-3, that had some excess fuel and negotiate a purchase of it. I told them I needed to do some thinking about this and that I was going into the hotel to relax and figure out what to do. Going into town, I noticed that within a block of where my airplane was parked there was an ESSO service station. So the next morning I went out and discovered that I could transfer about 5 gallons of autogas from my rental car into my auxiliary tank in about five minutes. It didn't take me long to get enough fuel to get to my next stop. I have talked to many people since then about the use of autogas for avgas. In 1969, at the request of the AOPA, I wrote an article on the subject. I have received hundreds of phone calls and letters from people saying, "tell me more." And right now there is nothing wrong with cruising with autogas in a 100 octane engine, like that in the Cessna 340 if you take off on 100 octane. Autogas has ample octane number for low cruise power. I don't know why one needs to cruise at more than 55 percent power. And you don't need very much octane for low power settings.

Tom Smith/Mooney: Are you suggesting that aircraft carry two types of fuel?

Al Hundere/Alcor: That is correct. There is nothing new about that. I worked with one of the freight carriers back in the late '40s that wanted to use multi-fuels--Slick Airways. I helped them conduct tests that certified the engines to be derated and use 91 octane. There was quite a bracket between 91 and 100 octane. For years, while we had the C-46s, they took off on 100 octane and cruised on 91 octane. And this, I think,

is something we'll have to do in the future. In order to use more than one fuel, at least in the older aircraft, we'll have to modify.

Bob Mount/Curtiss-Wright: Our recent experiences at Curtiss-Wright are based on rotary engine development. Currently we are developing an engine for the Marine Corps that will be in production and delivered by the latter part of the 1980s. One of the primary considerations of the military was the need for multi-fuel capability. This means the use of diesel fuel as the primary fuel, with gasoline and jet fuels as backup. Furthermore, our experiences with DOE, with the people in Detroit, with the other military agencies, and with NASA, have all indicated that there is a real need for multi-fuel capability. This is primarily why Curtiss-Wright has devoted its attention to the stratified charge rotary engine which can operate on these various fuels. We've operated rotary engines on diesel, gasolines, jet fuel and alcohol. We have demonstrated a rapid switchover from one fuel to the other. Anyone in this group is welcome to come and visit our facilities and see this multi-fuel capability demonstrated. In summary, we think a multi-fuel capability is a definite requirement for general aviation as well as in other aircraft.

Joe Rowe/General Electric: I represent the turbine industry. By their very nature, turbine engines are a little more forgiving of fuel characteristics than internal combustion engines and are inherently more adaptable to multi-fuel use. Of course, the problem is one of size, capability and cost. There is a lot of R & D going on and progress being made in aerodynamic design and related technology to reduce the size of engines at reasonable costs. From a size point of view, in the range of 400 to 600 horsepower, present engines are acceptable; but improvements are possible. By the late 1980s or early '90s, we may be able to develop a turbine engine in the 100 to 200 horsepower class with reasonable economy of operation and reasonable cost, but it will be difficult. Rather, I see turbine engine technology going in the direction of providing a competitive and viable power plant in the 400 to 600 horsepower range in this timeframe.

Tom Smith/Mooney: What is the primary drawback from getting down into the 200 to 300 horsepower range?

Joe Rowe/General Electric: It is economy. Small engines are not as efficient. Efficiency is related to the compressor pressure-ratio. As pressure-ratio increases, the size of the various components in the high pressure part of the engine gets smaller. And these size effects are very harmful. As a result, efficiency is compromised in order to get turbine power at very low levels. Notwithstanding, as we learn more about "end effects," develop new analytic tools to help us design, and develop new materials and processes to produce smaller airfoils with good finish and good contours, then this technology will improve. However, I do not envision the development of high efficiency, low horsepower engines much before the year 2000.

Joseph Schubeck/Stage II: On the West Coast, we have an exciting program underway, headed up by myself and a few others interested in financing the development of a liquid-cooled V-8 engine. Not to be associated with anything that is coming out of Detroit, this is an all-aluminum engine that is being cast in Los Angeles. We started this program at Stage II some five years ago. Originally, we set out to develop a more efficient liquid-cooled engine to run on avgas. At the completion of over 350 hours of flight testing, those putting the money up for certification decided to take another look into the future, and specifically at the possibility of using alternate fuels. We decided to put the gasoline version of the Stage II 650 horsepower engine on the back burner and, instead, develop new technology based on the diesel.

Now we are building hardware to start a program that is going to be called "Lightweight Diesel." We are looking at the possibility of using JP 4 and 5 and, of course, Number 1 diesel fuels. We are also considering multi-fuel capability. Where we used to use two spark plugs in our combustion chamber, we now have the capability of not only two spark plugs, but two nozzles and two fuel pumps--in fact, two independent fuel systems. Also, we are looking very seriously at a second priority, which is a compression-ignition engine that can fire and burn kerosene, jet fuel and turbine fuel. As a result, we can also utilize lower octane fuels such as alcohols, especially methanol, as a second fuel. Our engine would be an all liquid-cooled engine--not water, but a combination of water and glycol. In summary, we have had second thoughts about certifying engines which operate on gasoline only because the future of avgas is a bit questionable. As a result, we have undertaken a serious program which, depending on our success, will lead us to certification of these engines by 1985.

Cesar Gonzalez/Cessna: Mr. Schubeck, is your engine a spark-ignited diesel?

Joe Schubeck/Stage II: No, it is a compression-ignited engine. In the first development it was a spark-ignited engine designed to run on gasoline. Now we are making a complete turnabout and we are eliminating the ignition system, i.e., the spark plugs and all the related electrical systems.

Cesar Gonzales/Cessna: Aside from working at Cessna, I own and operate my own airplane. At these meetings I perceive that there are those who advocate the use of alternate fuels such as automotive gasolines, and there are those who are completely opposed to use of any fuel except avgas. To reconcile these views, we have to start with a clear understanding of the engines. There are engines that will accept certain automotive fuels and there are engines that will not. I believe that we should start talking autogas in lieu of avgas from an emergency fuel standpoint. Perhaps from that standpoint we can gain some new knowledge and insight. Right now, we talk with very few facts in hand. A major concern is to keep in the air those airplanes that are flying today. Maybe we should work toward a multi-fuel capability (or even use automobile fuel) for future engine design. If an emergency occurs, will we be ready for it and can we keep at least some of the fleet flying? I know from first-hand experience that the small Continental or Lycoming engines that were built in the early 1950's can use automotive gas. On the other hand, I almost killed myself and my entire family trying to operate an O-300 engine in a Cessna 175 on autogas. So, are there differences between engines and aircraft? If we lose sight of that, then we will not know what to do if an emergency situation arises. I believe that the issue is one of making a decision between taking some risks and keeping the plane on the ground. Let us put aside industry concerns and as concerned, knowledgeable individuals, decide what is best. Let us begin by considering autogas in lieu of avgas from an emergency viewpoint. On an emergency fuel basis, what can we do? What can the FAA do? What can everybody do? Let's pitch in and work, because when we work together, I see very few problems that are insurmountable.

Ed Beisser/Phillips: Phillips Petroleum markets a complete line of aviation products, including oils and jet fuels as well as aviation gasoline. I am a pilot, so I am torn by the avgas-autogas controversy. Yet I won't put autogas in my Cessna 310. Yes, there are going to be certain places, because of logistical supply problems, where there won't be any fuel. But by and large, there will be ample supplies of avgas strategically located throughout the United States. Now, I cannot talk about the Bahamas, but I think you can find avgas as you fly your general aviation airplane almost anywhere. I think that most of us who are in the energy business are committed to it. At Phillips we have dedicated ourselves to not entering the unleaded premium autogas market.

Unleaded premium really takes the alkylates, and those are the components needed to make 100 low-lead. As a marketing manager, I really enjoyed listening to the GAMA paper on just what the future looks like from the point of view of the airplane manufacturers, and what is going to happen. My concern, though, is that the more jet fuel we sell the more expensive it will become. At present there is no great differential in profitability selling avgas and jet fuel at the wholesale or retail level. One final point, I constantly look at profitability within our company; we are committed to it. We will not put motor gasoline at airports.

Paul Poberezny/EAA: What's a little guy? To me, a little guy is anyone, regardless of wealth, who pays his own way. All too often, EAA has been looked upon as a promoter of a particular product, because if it saves money or is safe it is worthwhile. We are first to recognize that in our society liability (or assuming the liability) is one of the greatest hindrances to new product development. How often I have met with the FAA folks over the last thirty years, and people in the industry for that matter, who could not talk from the heart as long as they were employed. But, boy, you should hear them after they retire! One of our greatest problems at EAA is lack of research information. I don't think anybody has all the answers at this stage. So our work is research. We are not promoting the use of alternate fuels or autofuels. Every document that we have ever prepared, including my latest homebuilders articles, argues research first--true research. How often do I get letters and telephone calls..."Paul, can we use autofuel?" I say, "You are asking the wrong person." EAA is doing its own research and we hope that we can motivate others to get together to look into the future.

And I'll tell you another thing. You can talk about your new technology all you want but if we lose general aviation now because we have sat on our duffs, then technology is not going to rebuild it. And to me, over 200,000 aircraft in the whole United States is peanuts. There are over 200,000 ground vehicles in the immediate Cleveland area. If you want to help the aviation industry you can stand up--get off your duff. We do our little share of trying to motivate and to find answers for something that we have been grasping for--not to say it cannot work. If I would believe all the citizens that wrote to me telling of their great success using all sorts of fuels, then a lot of people are way ahead of us. One gentleman who operates an FBO wrote to me and said that he has over 35,000 hours on his helicopters, his twins, and his single engine airplanes using autogas. Another FBO operator wrote to me and said that he had sold autogas at his FBO from 1940 through 1968. Now, what do I do with that information? What can you do? I think the true test is to really start taking a methodical look-see and get into developing well thought out programs. What are our backups in the event that we don't have any readily available fuels? As an owner of five airplanes, none of them are worth anything to me with empty tanks. Another point that was touched on today was the safety aspects of using autogas. As you may know, the average pilot only flies about forty hours a year. Let us recognize their safety record. How good would we be if we were to only drive our cars forty hours a year in snow, fog, rain and sleet?

Les Waters/Teledyne: We talked this morning about combustion systems for the future. Now I will address the multi-fuel aspects of that. If we look at the 1950s and 1960s, titanic efforts were made in the States and in Europe to achieve multi-fuel capability, mostly in diesel engines. This was done under the motivation of military incentives. Despite all that work, the results weren't really successful. Moreover, they weren't successful in terms of what we are looking for in aircraft engines; that is, the specific performances, weights and fuel consumptions were not competitive with contemporary piston engines. In the last decade, automotive gasoline type combustion systems got a shot in the arm with the arrival of EPA requirements. Recently a lot of

work has been done on systems that are octane and/or cetane insensitive. In terms of new commercial products, they have not been attractive due to smoke limitations or poor air utilization, resulting in low specific performance. It seems to me that the high specific performance necessary in the new aircraft systems is most unlikely to be obtained if we impose a multi-fuel capability as well. Our efforts must be devoted to achieving equal or superior performance using turbine fuel and I think that even going to a single fuel is going to be a tough enough task. We shouldn't be looking at a multi-fuel capability also.

LIGHTWEIGHT AIRCRAFT ENGINES, THE POTENTIAL AND PROBLEMS FOR USE OF AUTOMOTIVE FUELS

Donald J. Patterson
University of Michigan

INTRODUCTION

Over the years many pilots have reported on an informal basis that they have successfully used automotive gasoline (autogas) in their light aircraft. On the other hand, use of autogas is suspected to have caused engine malfunctions, some of which may have resulted in crashes. This presentation summarizes a recent report to the FAA in which this dichotomy of views is evaluated in terms of characteristics of autogas and aviation gasoline and how the differences might be expected to affect safety, engine performance and durability.*

Several key fundamental areas have been explored. These are:

Antiknock properties
Preignition and deposit ignition
Vapor lock
Icing
Cold start
Hot restart
Fuel safety
Valve sticking and wear
Materials incompatibility and corrosion
Maldistribution
Spark plug operation
Fuel storage stability

Below are presented the overall conclusions of the FAA sponsored study. Detailed conclusions follow in the next section.

OVERALL CONCLUSIONS AND OBSERVATIONS

1. Based upon existing information, the use of autogas in light aircraft is expected in general to create safety problems. It is obvious that some aircraft and some batches of autogas will perform satisfactorily depending on ambient temperature,

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*The remarks of Professor Patterson were intended as a summary of the more detailed report, "Light Aircraft Engines, The Potential and Problems for Use of Automotive Fuels, Phase I - Literature Search," FAA-CT 81-150, Dec. 1980. A copy was provided to each workshop attendee.

altitude attained, mode of operation, and fuel system design. Under other circumstances serious problems can arise quickly and there is considerable potential for longer range problems of materials and engine durability which may or may not create a dangerous problem.

2. Many of the technical studies of aircraft fuels have been conducted during or prior to World War II, and therefore are relatively old. Few recent studies exist. There is considerable lack of data on just how fuel property variations affect the performance and durability of aircraft engines. This situation does not support conclusions in many areas.

3. Based on available information it cannot be determined with certainty that future engine/aircraft designs can be developed that will be entirely tolerant of the widely varying properties of autogas, properties whose variations are steadily growing as refiners attempt to maximize gasoline yield in reponse to higher prices. Research needs to be done to further delineate key problem areas and potential solutions. Standard tests need to be developed by which new fuel system designs can be evaluated. Such tests may employ a set of standard fuels whose properties reflect those of autogas which has wide variations season to season and from one part of the country to another. If aircraft can be developed which are compatible with autogas, they are likely to be more complex and expensive than current models.

DETAILED CONCLUSIONS

1. There is only one grade of avgas that can be replaced by autogas because of antiknock quality, that is grade 80/87. Regular, premium and lead-free automotive gasolines all appear to have sufficient motor octane quality. The lack of a general correlation between the Aviation Supercharge and Automotive Research octane numbers precludes any decision with respect to this rating, although some evidence exists which suggests that the autogas Rich rating is adequate for grade 80/87.

2. Use of autogas with its higher aromatic content and higher volume of low boiling point constituents is expected to increase combustion chamber deposits which in turn can aggravate knock-induced preignition. Moreover, it is known that some aromatic compounds tend to preignite easily. Some engines are likely to have greater preignition problems depending on cylinder cooling. The heating value specification for avgas effectively limits its aromatic content to about 25%.

3. Vapor lock is known to be a problem occasionally even with avgas which has maximum Reid vapor pressure of 7 lbf/in^2. With autogas, the maximum Reid pressure can approach 16 lbf/in^2, and this increases the likelihood of vapor lock considerably. This problem is greater for a low wing aircraft and might be ameliorated by a suitable intank fuel pump. Vapor lock is probably the most important safety-related problem needing solution before autogas can replace avgas.

4. Carburetor icing appears to pose a somewhat greater problem with autogas than with avgas. Some improvements in icing can be realized by the addition of anti-icing compounds to those fuels not already containing them.

5. Although specific data are not available for aircraft, a consideration of the automotive literature indicates that the higher front end volatility of autogas can be expected to ease starting and warmup in cold weather operation.

6. Hot restart on the ground may be expected to be more difficult with autogas because of increased deposit ignition and vapor lock. Significant differences are expected at altitude also when vapor lock is present.

7. A search of the literature reveals that gasolines with high boiling point constituents (autogas) create greater problems of valve sticking and valve guide deposits. These arise from contamination of the lubricant and/or deposits of unburned fuel components on the valve stems and guides themselves. More sludge and varnish are expected in the crankcase with autogas. This results from high blowby rates in aircraft engines and relatively low detergency in the oil.

8. The greater aromatic and olefinic content of automotive gasolines is known to adversely affect the performance and durability of polymeric and rubber fuel system materials. Problems arise when critical dimensions are exceeded and parts stick, or when physical properties are deteriorated.

9. The greater sulfur level and higher levels of halogen scavengers in autogas can be expected to increase acid corrosion of the engine, a long term durability problem.

10. There is no data to indicate the severity of valve seat recession problems in aircraft engines when lead-free autogas is used.

11. Maldistribution may be expected to be worse with autogas due to its greater boiling range. This can lead to engine roughness, knock and removal of lubricating oil from cylinder surfaces under low temperature operation. There is no indication of a safety problem from this source.

12. Spark plug fouling is expected to be increased with leaded automotive fuels because of their greater volume of high boiling point constituents and higher lead levels. With lead-free gasolines, spark plug fouling will be reduced compared to some aviation gasoline due to the absence of lead compounds.

13. For equal storage time and temperature, storage stability is worse with autogas. This can contribute to increased gum with subsequent intake valve sticking and carburetor orifice plugging. Avgas is provided with a relatively high dosage of anti-oxident to delay gum formation. On the other hand, use of fresh autogas will pose no gum problems and to the extent that fuel storage times are reduced because of a high turnover of autogas, perhaps gum problems would be reduced in practice.

14. Fuel safety in regard to toxicity and explosion hazard is about the same for all these gasolines.

SUMMARY, PROBLEMS, AND SOME POTENTIAL SOLUTIONS

In the preceding sections several problems were discussed associated with matching gasoline fuels to engines. Much information is available for automotive systems and relatively little for aircraft. Table 1 summarizes the problems discussed and indicates differences between avgas and autogas and the nature of the problem. In terms of antiknock quality, all autogases meet the lean requirement of grade 80/87 avgas, and probably meet the Rich requirement as well, but this cannot be proven at this time. Autogas antiknock quality is far too low to satisfy the higher avgas grades. In

one problem area only is there a large difference between avgas and autogas; that is vapor lock. With the exception of icing, the other problems are relatively moderate, and may be circumvented by more frequent maintenance including oil changes.

Filter and fuel line freezing problems can be alleviated by the addition of anti-icers and by careful draining of tank bottoms. Carburetor icing can be controlled by suitable air preheating, a common practice on modern automobiles.

The vapor lock problem is most difficult to solve. In terms of fuel metering two possibilities present themselves. One is to fully and continuously evaporate the fuel prior to metering and thus entirely circumvent the problem associated with metering evaporating fluids. For this, a separate system is required for starting and warm-up until exhaust heat is available for vaporization. The other possibility is to employ high pressure individual cylinder port fuel injection or single point injection above the throttle body. In this way, solid fuel is metered and the large pressure drop at the nozzle assures that liquid fuel is in the lines. One advantage of single point injection is that the injector is removed from the hot intake port. Continuous recirculation of the fuel back to the tank can be used to keep injectors cool and vapor return to the fuel tank used to eliminate injector vapor problems. Some invention and development is required to provide entirely adequate systems of either type.

The vapor lock problems associated with fuel line and pump volume can be alleviated by a combination of:

1. Larger diameter lines
2. In-tank pump
3. Routing of lines for minimum heat pickup.

Centrifugal in-tank pumps have good potential for minimal suction pressure drop, high pressure and high flow. Perhaps more than one stage is required depending on pressure requirements or two pumps in series of different design.

By employing advanced technology, future aircraft may be built to be insensitive to the widely varying properties of autogas, properties whose variations appear to be increasing as refiners attempt to improve refinery efficiency. The use of oxygenates as supplements in autogas opens up a new degree of autogas variation and is likely to introduce severe material problems both in automobiles and aircraft whose materials have not been selected for use with these blending agents initially.

Use of automotive oils with their greater capability for neutralizing acids and their improved detergent and dispersant properties could alleviate problems produced by increased sulfur and higher volumes of high boiling point constituents in autogas. However, the large blowby and oil consumption rates of aircraft engines must be reduced through improved design to minimize oil contamination and to minimize combustion chamber deposits from the ash-forming additives of automotive oils. A Wankel engine has an advantage in this regard in that the lubricating oil is isolated from the blowby.

In order to provide a basis for change, it may be desirable to design a standard fuel system certification test. Such a test may be similar in concept to the ASTM Sequence Test for automotive lubricants, but rather employ standard lubricants and standard test fuels representative of the extremes of expected autogas properties and composition. Engines and fuel systems thought to be most sensitive would be used as test beds. Obviously, considerable effort will be required to design appropriate

tests; but in the absence of established procedures as a baseline, it will be difficult if not impossible to effect any change in the status quo.

TABLE I. - PROBLEM SEVERITY COMPARISON

Problem	Severity Difference between Autogas and Avgas	Suddenness of Onset
Immediate, or Short Range		
Knock	Little	Rapid
Preignition	Moderate (worse)	Very Rapid
Deposit Ignition	Moderate (worse)	Rapid
Vapor Lock	Large (worse)	Rapid
Icing - Carburetor	Moderate (worse)	Rapid
- Filters & Lines	Moderate (worse)	Rapid
Cold Start	Moderate (better)	Rapid
Hot Restart	Moderate (worse)	Rapid
Spark Plug	Moderate (better w unleaded) (worse w leaded)	Rapid
Fuel Safety	Little	Rapid
Long Term		
Driveability (Maldistribution)	Moderate (worse)	Continuous
Valve Sticking and Wear	Moderate (worse)	Very Gradual
Compatibility with Materials & Corrosion	Moderate (worse)	Very Gradual
Lubrication and Wear	Moderate (worse)	Very Gradual
Storage Instability	Moderate (worse)	Rapid

GENERAL AVIATION FUEL QUALITY CONTROL

Herbert Poitz
Shell Oil

Quality control on aviation products, especially turbine fuel, is a subject that we could talk about for the rest of this meeting. In order to eliminate turbine fuel from the picture, I will speak only on quality control measures for aviation gasoline, and some of the differences between quality control on avgas and mogas. One thing to keep in mind is that with motor gasoline you can always pull off to the side of the road. It's not so easy to do in an airplane. Consequently, there are reasons for having the tight specifications and the tight quality control measures on avgas as compared to motor gasoline.

To show you how important we considered it, we've devoted an entire small booklet to the subject on how to handle aviation fuel. This is one of our best sellers; we give it to our dealers.

The special quality control on aviation gasoline begins at the refinery. A full set of ASTM tests is run on every batch of fuel before it leaves the refinery. All properties are covered. Then the fuel moves through the distribution system out to the field to a distribution plant. There a sample is taken, sent back to the refinery, and the full manufacturing specifications are rerun. If there is any variation, the tankful is deemed bad fuel and must be used elsewhere. Often it is put into motor gasoline, at least it used to be. However, it can't be put into the unleaded grades, and we're running out of premium and house brands. So we may have a problem getting rid of off-spec avgas one of these days. From the distribution plant, the avgas is moved to a FBO, and from the FBO to the end user, the airplane driver.

Figure 1 is a list of the properties that are tested on every batch of avgas before it leaves the refinery, and again when it gets to the distribution plant, when a sample is sent back to the refinery. On non-aviation products we sometimes obtain waivers on certain properties that we deem are not too important. We never get waivers on any aviation products. They stay there until they are right, or they don't move out. Once in a while the manufacturing plant pulls a fast one. We usually catch it out in the distribution plant, and have to get rid of it by putting it into motor gasoline. But we never knowingly give waivers against an ASTM specification on any aviation gasoline product.

You can see from Figure 1 that a sizable amount of testing is done before a batch is released. Then it goes into presegregated delivery out to the distribution plant, where again a sample is taken and these same properties are run back at the refinery.

In addition to this, our distribution plants make receiving inspections. Most have the facilities for running flash point and gravity. Color, of course, is pure and simple. Water is determined by visual inspection using the "white bucket" test. It consists of finding a white thunder-mug or a white enamel bucket, and drawing about a one gallon sample of the product into the bottom. The fuel is then stirred and observed for clarity and dirt in the bottom of the bucket. It's a very scientific test. You can

really sort out a lot of things with that white bucket! Of course, after about two months of kicking around, it's no longer white and hasn't got any enamel and you have to start all over. Don't try it with a white plastic bucket; that doesn't work.

In the plant, in addition to these receiving checks and the fact that the product sample is sent back to the refinery, daily, weekly and monthly checks are run on the facility itself. The water bottoms in the storage tank are checked and water drawn off every day. Enough product is drawn to make sure that it is the right color and is clean, clear and bright.

Then the product moves from the distribution point, the petroleum distributor point, out to the FBO. The FBO on receipt of his delivery, runs the white bucket check again, and observes the clarity of the product. It should be clear and bright, and the right color. Hopefully he doesn't do like a few people have, received motor gasoline and complain that it's sort of an unusual shade of green or blue, when it actually was yellow. We've had a few of them do that. It costs us about six or seven thousand dollars per engine because they don't run too well on motor gasoline when they're supposed to operate on 100 octane. We have had a few other cases where the receiver received a load of turbine fuel into the avgas storage and didn't realize that it wasn't the right color. Turbine fuel is essentially colorless. That cost us a quarter of a million dollars, because they don't fly very well on a mixture of avgas and turbine fuel. Theoretically the FBO is supposed to be there when they receive a load of fuel into his storage tanks and check out what he's getting and make sure that it is clear, bright, and dry, and doesn't have a bunch of dirt in it.

The last area of quality control is the aircraft pilot himself. When he is receiving a load of fuel, good pilots pull a quality control check themselves. They make sure of what color product is going into the wing tanks, and they pull a water sump check before they take off.

At some point in the avgas distribution system, and preferably as close to the aircraft as possible, there is a filter. In every avgas installation there is a filter. It may be on the refueler, it may be on the filling station-type dispenser, but there is a filter. This is a significant difference between mogas and avgas, because other than some people who tried full flow filters on their nozzle ends years back (as soon as they plugged up the mechanics punched a screwdriver through them and left the cartridges in there), there is a filter in your avgas installations.

We feel so strongly about quality control that every six months a qualified inspector, usually one of our commercial salesmen, stops by one of the FBOs, usually one of the ones he's responsible for, and does about a four-hour quality control equipment check. He checks over all of the equipment, and inspects the water sumps in all of the tanks to make sure there's no water in the storage tanks. He also has the operator pump enough fuel to be sure that all the in-line screens are in place and that the filter's in place. We do this every six months, and I'm sure that all of the other oil companies have some program similar to this.

The end result is a quality product which conforms to the long list of inspection properties in Figure 1. For comparison Figure 2 shows the inspection test properties that are run on motor gasoline. This is done only once clear back at the refinery level. There are no further properties determined on that sample of mogas before it goes into your car. The filling station operator does check his tanks for water. That's about it. There are no further quality control checks run at the retail level. After the product leaves the refinery, the only other check in the distribution plant is for

clarity, clear and bright, and that's about it. They do retain a sample in case there are some problems later on down the line, but these are not sent back to the refinery and rechecked with the great thoroughness that we do on avgas.

Figure 3 is a comparison of the avgas and mogas testing properties. I think the significant thing here is that in the right-hand column under mogas is the large amount of "Not Run" notations. This gives a good comparison as to what we do on avgas and what we don't do on mogas. I don't mean to indicate by this that you should not buy motor gasoline, because as we said avgas only represents about 1/4 of a percent of our product. So don't cut us out just because we don't run all of these quality control tests. But there is quite a difference between what we do do on avgas and don't do on motor fuel.

Figure 1

INSPECTION TESTS FOR AVGAS PROPERTIES

Gravity, specific at 60° F

Color

Odor

Aniline-Gravity product

Heat of Combustion, BTU/lb. (Net) (Calc)

Freezing Point, °F (D-2386)

Water Reaction

- Increase or Decrease, ML
- Interface Rating

Anti knock Rating, Motor Performance Number

Anti-knock Rating, Supercharge Performance

Number Tel, ml/gal

Inhibitor, lb/1000 ml

Gum, Accel Aging 16 hrs. mg/100 ml

- Precipitate, mg/100 ml

Gum, existent (air jet), mg/100 ml

Sulfur, %wt

Doctor Test

Corrosion, CU strip bomb at 212°F

Distillation

- IBP, °F
- 10% Evaporated, °F
- 40% Evaporated, °F
- 50% Evaporated, °F
- 90% Evaporated, °F
- End Point, °F
- Recovery, %V
- Residue, %V
- Loss, %V
- Sum of 10 and 50% evap. temp., °F
- Acidity of Residue

Figure 2

INSPECTION TESTS FOR MOGAS PROPERTIES

Gravity, ^{o}API @ 60^{o}F

Color

Octane No. Research

Octane No. Motor

Octane No. R+M/2

Lead, grams/gallon

RVP, lbs

ASTM Gum, mg/100 ml

Sulfur, %wt

ASTM Distillation, ^{o}F

- IBP
- End Point
- 10% Evaporated
- 50% Evaporated
- 90% Evaporated

TV/L 20^{o}F (calculated)

Mercaptan Sulfur, %w

Figure 3

COMPARISON 100 LL AND PREMIUM MOGAS

GRADE	100/130	MOGAS
Gravity, Specific at 60°F	.7165	.749
Color	Blue	Red
Odor	Pass	Not Run
Aniline-Gravity Product	9.015	Not Run
Heat of Combustion, BTU/lb. (Net) (Calc)	18,832	Not Run
Freezing Point, °F (D-2386)	B-76	Not Run
Water Reaction		
Increase or Decrease, ml	1	Not Run
Interface Rating	1B	Not Run
Motor Rating, Motor Performance Number	105.0	86.8
Motor Rating, Supercharge Performance No.	135.1	Not Run
Tel, ml/gal	1.57	1.54
Inhibitor, lb/1000 BBL (Ionol)	4.0	None
Gum, Accel Aging 16 hrs. mg/100 ml	1	1.1
Precipitate, mg/100 ml	Clear	-
Gum, Existent (Air Jet), mg/100 ml	1	Not Run
Sulfur, %W	L.01	0.3
Doctor Test	Negative	Not Run
Corrosion, Cu Strip Bomb at 212°F	1	Not Run
Vapor Pressure, Reid, LB at 100°F	5.7	8.6
Distillation		
IBP, °F	118	93
10% Evap., °F	165	118
40% Evap., °F	207	-
50% Evap., °F	211	212
90% Evap., °F	241	360
End Point, °F	314	409
Recovery, %V	97.5	-
Residue, %V	1.0	-
Loss, %V	1.5	-
Sum of 10 and 50% Evap. Temp., °F	376	-
Acidity of Residue	Neutral	Not Obtained

MANUFACTURING COMPARISONS OF AVIATION AND MOTOR GASOLINES

Lawrence O. Meyer
Phillips Petroleum

My talk today compares the manufacturing of avgas with that of autogas.

In my comparisons, I will tell you how we make 100/130 low lead avgas at Phillips. I will also cover information on the two principal components that are used in making our avgas. These components are alkylate and what we call a heavy platformate, which is almost entirely aromatics, principally toluene. In two of my slides I will show how we make those two principal components. Also, I will present information on how avgas compares to autogas with respect to antiknock quality and volatility characteristics. Finally, I will summarize what I consider to be the principal differences between avgas and autogas.

My first slide, Chart No. 1, presents a typical composition for the 100/130 low-lead avgas we produce. Isopentane, the first component listed, is used at 12% to meet the vapor pressure specification for aviation gasoline. The second component, alkylate, is the principal one, with a concentration of 61%. The third component, heavy platformate, is primarily toluene with a concentration of 20%. The final component in the blend is an iso-paraffin called isohexane which, at 7%, is necessary to obtain the distillation characteristics needed to meet volatility specifications.

In addition to composition, this first slide presents the lean and rich rating qualities of the blend stocks. Lean and rich ratings are both expressed as octane number below 100 and performance number above 100. Performance number is a power rating. You will notice that there is a difference in the lean and rich quality of these components and that the only one with a lean rating above 100 is alkylate. The only one that provides a value above 130 performance number on the rich rating side is heavy platformate. Its rich rating value is 202. Both of these stocks are necessary to make both the lean and rich rating qualities of 100 and 130 respectively.

At the bottom of the chart I've shown the finished antiknock quality of the fuel. It has 103.3 performance number lean and 131.8 performance number rich. Actually, our performance number lean is higher than needed. It is necessary to do this in order to make the rich rating.

I would also like to mention the relationship between milliliters of TEL and grams of lead. One milliliter of TEL is equivalent to 1.057 grams of lead. It's almost 1 to 1. At the bottom of the Chart is also listed a variety of stocks used in making motor fuel. These stocks are so low in quality that they do not qualify for use in making 100/130 aviation gasoline.

Does the motor alkylate versus the alkylate have anything to do with the method of producing these products?

Yes, I think the next slide will answer your question. This slide, Chart No. 2, shows how we make alkylate. In this diagram, we start out with crude, in the upper left hand corner, and show the movement of the process by arrows in a zigzag fashion from

left to right or right to left. As shown in the upper left hand corner, the crude is fed into the Fractionater. One of the products from the Fractionater is a light straight run which is used as a motor fuel stock. The other products from the Fractionater are gas oil and topped crude, both of which are fed into the Cat Cracker. One product from the Cat Cracker is light olefins, which is fed into the HF Alkylation Unit. The HF Alkylation Unit produces what we call the total alkylate or motor fuel alkylate, which Ed Beiser mentioned earlier. Along with the total alkylate is produced some normal butane which is removed by the Debutanizer shown in the lower left hand corner. From the Debutanizer the alkylate is fed to the Alkylate Splitter. In this final step, the total alkylate is split to produce aviation alkylate, a lower end point, lower boiling material, and also a heavy alkylate.

At the bottom of this slide is shown that in refiner operations, 1.25 barrels of natural gas liquids are used along with every barrel of crude. From these two feed stocks is obtained approximately 28% cat crack, 8% light alkylate, 1% heavy alkylate, and the remainder being distillates.

In the next slide, Chart No. 3, is shown how we manufacture platformate. The feed stock is natural gas liquids, a light material. This feed stock is fed into a catalytic reformer which has a platinum catalyst. The product from this unit is called platformate. It is necessary to feed this product into a splitter to obtain the heavy platformate which is needed as a high, rich-rating avgas component. Light platformate, the other product from the splitter, is used for motor fuel. From a barrel of NGL, shown at the bottom of the Chart, is obtained roughly 14% isopentane, 2% heavy platformate, 3% light platformate, and some LPG products, which could be propane, normal butane, etc.

In the next slide, Chart No. 4, I might be plowing some ground that's already been plowed, but please bear with me. This slide presents a comparison of the rich-rating quality and also the lean-rating quality of aviation gasoline versus today's motor fuel. Two grades of avgas are shown, 80/87 and 100/130. In describing the antiknock quality of an avgas, such as 80/87, the 80 value is its lean rating and 87 its rich rating. Lead contents for the avgas are also shown. Data for two groups of unleaded auto gas are shown. The first group represents unleaded regular with an $(R+M)/_2$ of less than 90. The second group is unleaded gasoline of greater than 90 $(R+M)/_2$ antiknock quality and represents unleaded premium. Lastly, leaded regular is shown. To obtain representative rich ratings for these three groups of autogas, market samples of these products were rated in a supercharge engine to obtain their supercharge rich ratings. The lean octane ratings for the motor fuels are easily obtained from their motor rating. It can be noted that the unleaded regular has lean and rich octane qualities of 82.8/87, the unleaded premium has values of 86.8/91, and the values for leaded regular are 84.8/90. All three groups of motor fuel have aviation rating qualities better than 80/87. However, none of them make 100/130. It is significant to mention that the aromatic contents of the unleaded motor fuel groups are higher than normally found in avgas. Avgas aromatic content is limited by heat content, Btu per pound. Actually, avgas heat content specifications limit their aromatic content to approximately 25% aromatics. As shown in Chart No. 4, the unleaded premium motor fuels have an average aromatic content of 36%. In some cases, it has been found to be as high as 50%.

Professor Patterson has previously presented data on the volatility characteristics of avgas vs. autogas. In this slide, Chart No. 5, is shown the difference in volatility specifications between autogas and aviation gasoline as given in the ASTM specifications. In addition to maximum temperatures for the 10%, 50%, 90% and end point are shown the vapor pressure limitations. It can be noted that it could be possible to

make motor fuel out of avgas by increasing the vapor pressure. However, it wouldn't be possible to go the other direction since the vapor pressures of motor fuels are higher than the aviation gasoline vapor pressure specifications. In the last line of the chart are shown ASTM ES-5 Motor Fuel Specifications. This is an emergency specification. It is a motor fuel emergency specification which, after we had the energy crunch, was developed to increase motor fuel production. At that time it was decided that if 9 more degrees were added to the 90% temperature, 9 more degrees to the end point, and the vapor pressure increased a little more, we could increase production. Actually, the emergency specification, ES-5, and the standard specification for motor fuel are not greatly different.

In my last slide, Chart No. 6, is shown what I consider the main differences between avgas and motor fuel. First, there's vapor pressure. Other principal differences are distillation characteristics, antiknock quality, lead content, heat content, color, aromatic content, and I might even add additives. I might reemphasize the importance of heat content. In the case of unleaded premium it was mentioned that the average aromatic content was in the range of 36%. This poses the question of whether or not the lowering of the heat content by increasing aromatic content may affect the performance characteristics of unleaded premium if it were used as avgas.

CHART NO. 1

CHARACTERISTICS OF TYPICAL 100LL AVGAS

ANTIKNOCK QUALITY WITH 2.0 mlTEL/GALLON**

Blend Component	ASTM Aviation Lean Rating*	ASTM Supercharge Rich Rating*
Isopentane, 12%	96.3	96.6
Alkylate, 61%	113.8	123.5
Heavy Platformate, 20%	96.0	202
Isohexane, 7%	94.5	94.7
Finished Blend	103.3 PN	131.8 PN

*Avgas ratings are expressed in octane number below 100 and in performance number (PN) above 100.

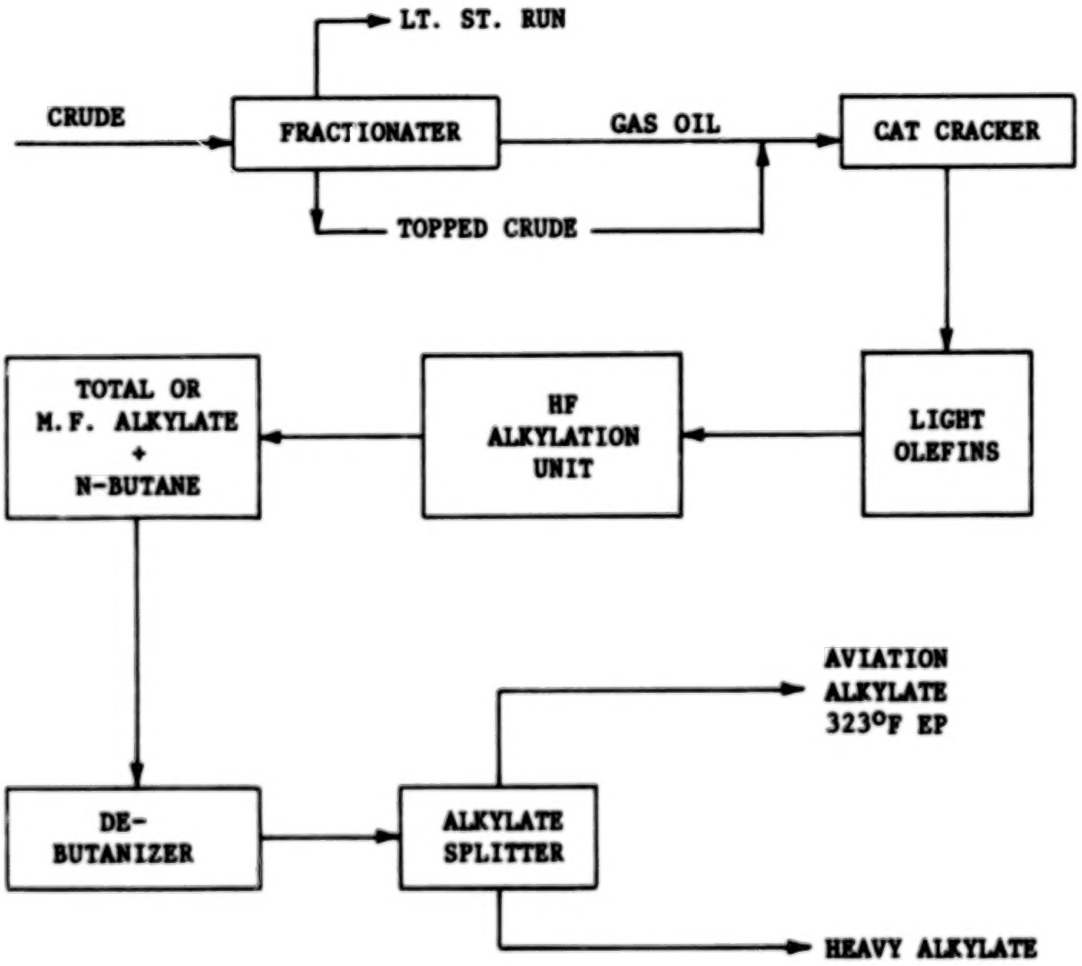
**1 mlTEL = 1.057 grams of lead.

TYPICAL MOTOR FUEL BLENDING STOCKS

Straight Run	Motor Alkylate	Isopentane
Cat Cracked	Platformate	Normal Butane

CHART NO. 2

ALKYLATE MANUFACTURE



APPROXIMATE VOLUMES

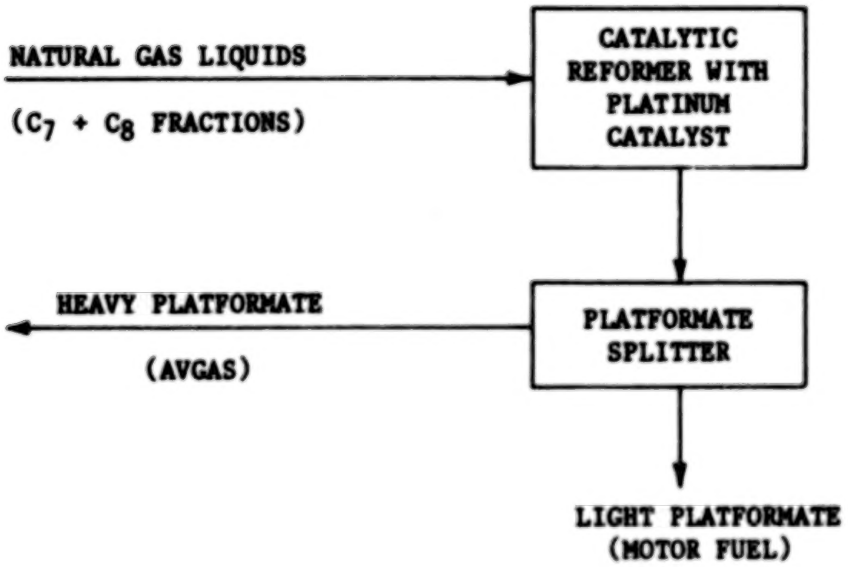
1 BARREL CRUDE
+
1.25 BARRELS NGL

→

28% CAT CRACKED +
8% LIGHT ALKYLATE +
1% HEAVY ALKYLATE +
DISTILLATES

CHART NO. 3

PLATFORMATE MANUFACTURE



APPROXIMATE VOLUMES

1 BARREL NGL → { 14% ISOPENTANE + 2% HEAVY PLATFORMATE + 3% LIGHT PLATFORMATE + LPG PRODUCTS

CHART NO. 4

FUEL QUALITY COMPARISONS

(Avgas Versus Autogas)

	Lean Rating, Octane No.	Rich Rating, Oct. No.	Rich Rating, Perf. No.	Lead Content, g/gal.	Aromatics Vol %
Avgas					
80/87	80	87	--	0.5 max.	--*
Avgas					
100/130 (2 grades)	100	--	130	2.0 or 4.0 max.	--*
Unleaded Autogas(1)					
Samples 90 (R+M)/2	82.8	87	--	--	29
Unleaded Autogas(2)					
Samples 90 (R+M)/2	86.6	91	--	--	36
Leaded Autogas(3)					
Regular	84.8	90	--	1.18	25

(1) Average of 82 samples, Summer 1980.

(2) Average of 15 samples, Summer 1980.

(3) Average of 77 samples, Summer 1980.

* Limited to approximately 25% toluene by minimum heating value, benzene limited to 10% by 280°F boiling point.

CHART NO. 5

ASTM VOLATILITY SPECIFICATION COMPARISONS

(Avgas Versus Autogas)

	10% Temp. F, Max.	50% Temp. F, Max.	90% Temp. F, Max.	EP Temp. F, Max.	Vapor Pressure Pounds, Max.
Avgas*					
(D910)	167	221	275	338	5-7
Autogas					
(D439)	122(1)-158(2)	230(1)-250(2)	365(1)-374(2)	437	9(2)-15(1)
Autogas					
ES-5(3)	122(1)-158(2)	230(1)-250(2)	374(4)-383(4)	446(4)	9.5(5)-15(5)

(1) Extreme for winter, northern climates (E)

(2) Extreme for summer, high altitude areas (A)

(3) Emergency Specifications

(4) Leaded only, unleaded same as D439

(5) Applies to both leaded and unleaded

* Grades 80/87 and 100/130

CHART NO. 6

PRINCIPAL QUALITY DIFFERENCES BETWEEN AVGAS AND AUTOGAS

VAPOR PRESSURE

DISTILLATION CHARACTERISTICS

ANTIKNOCK QUALITY

LEAD CONTENT

HEAT CONTENT

COLOR

AROMATIC CONTENT

ASTM AND ITS ROLE IN GENERAL AVIATION FUEL

Charles T. Stone
Exxon

I would like to discuss the function of ASTM, particularly Section II, which deals with aviation gasoline specifications.

For years, aviation gasoline was sort of a tail-on behind jet fuel, to the point that we almost lost sight of it completely. Consequently, Section II was set up. The function of ASTM Section II was to come up with a specification to serve as a guide for the quality control work we heard about previously. We all understand that the problem is flight safety. But you've got to have road markers to show you where to go. So ASTM provides the "road markers." This is basically the list of tests, as Herb Poitz has explained, that have to be run--not only run, but run repeatedly, on every batch of fuel that goes out. There is a key point that I hope you will keep in mind in dealing with the availability side of the question, and that is that if a product is off-spec, you shut down the tank. You don't deliver it, you shut it down.

So all this derives from the action of ASTM. These tests have been developed over the years as required to provide a flight-safe fuel. This list is modified from time to time. We're just in the process now of dropping one test that was found to be unnecessary. It didn't serve any purpose. We will add tests when, as, and if we should find an area that requires a tighter control. And that's the function of ASTM. In addition to this laundry list of tests to be run, for every one of these there is a matching test method. You not only run the test, but you run it by a precisely spelled-out method. And you interpret the results in a precisely spelled-out manner. I believe that ASTM performs a very valuable function largely related to the flight safety aspect of aviation gasoline.

The other thing that I find unique is that the engine builder, the airplane builder, the fuel suppliers, and the consumers all sit down and butt heads until they get something hammered into shape. It's kind of interesting to see that so many of the same faces who have worked so hard on these specifications over the years are all sitting here in this room.

FUEL SUPPLY AND DISTRIBUTION--FIXED BASE OPERATION

Lawrence C. Burian
National Air Transportation Association

INTRODUCTION

Feast to Famine

As recently as the late 1960s, aviation fuels -- like motor gasoline and other petroleum products -- were plentiful and cheap. In fact, to stimulate business, oil companies frequently provided aviation fuel retailers (FBOs) with fueling equipment, fuel farms, signs and promotional materials at little or no cost -- all for the purpose of acquiring business and getting their "branded" fuel into the marketplace. A very similar situation existed in the motor gasoline arena, where, as you remember, it was commonplace to receive trading stamps, china or glasses with each fill-up.

The 1973 Arab Oil Embargo changed all that. Overnight the marketplace changed from plentiful supplies at low prices to tight supplies at higher prices. To make matters worse, the government got involved, imposing mandatory price and allocation controls on aviation fuels. The impact of Uncle Sam's intervention meant all oil company/FBO relationships in effect on May 15, 1973 (a date arbitrarily picked by the government), were to remain in place for the duration of the control period that ended February 26, 1979.

Aviation Gasoline vs Other Products

Nearly everyone knows that with current use of our technology, motor gasoline cannot be safely used in a piston engine airplane. But at the refinery level, avgas has to compete with mogas for its share of the crude oil barrel. When compared to other petroleum products, especially motor gasoline, the quantity of avgas refined is very, very small. In fact, in 1979, aviation gasoline accounted for only one-fourth of one percent of all refined products in the United States. To produce this supply, refineries sometimes blend avgas for only several hours and end up with a full month's inventory. Therefore, it is understandable that many refinery managers tend to avoid avgas production because it interferes with other refinery operations.

A very complex system of common carrier pipelines exists to distribute petroleum products across the country. However, since avgas is produced in such small quantities and at only a small number of locations in the U.S., most pipeline companies will not accept it for shipment. Thus, the only other methods available to get the product from refineries to FBOs are barges, rail systems, and tank trucks -- all three of which are much more expensive than shipment via pipeline.

Changing Marketplace

Many people blame the decontrol of aviation fuels for the current price and supply situation. Let's take a look for a minute, however, at some of the real reasons for the current situation.

Prior to the imposition of controls, that is, in the early '70s, oil companies were beginning to realize it was uneconomical for them to be in the fuel farm and tank truck business, and impractical for them to offer such incentives to sell their products. So they began to sell the very sophisticated and expensive trucks and fuel tanks they had previously loaned or leased at low cost to FBOs. But when controls were imposed, one stipulation of the controls was that all suppliers were prohibited from requiring FBOs to purchase fueling equipment, or changing their relationship in any way.

This prohibition remained in effect until controls were lifted in early 1979, at which time suppliers jumped at the chance to realign their marketing strategies and make every profit center exactly that ... a profit center. Had there been no controls, or had the control period been of shorter duration, this realignment of marketing strategies would have still taken place, but would have been spread out over a much longer period of time. Thus, the transition we are now going through would have been far less traumatic.

TODAY'S PROBLEMS

Airline Deregulation Act of 1978

On October 24, 1978, the "Airline Deregulation Act of 1978" was signed into law. Passage of the Act represented the culmination of many years of study, discussion and hard work to forge a major legislative action which would completely change Government-industry relationships developed over 50 years. The Act represented the beginning of a new era for the American air transportation industry. The principal objective of the Act was to reduce government-economic regulation of the U.S. domestic air carrier industry by 1985. The air carriers were to operate virtually unencumbered in a competitive environment, subject only to the anti-trust and similar laws applicable to all U.S. industries. The full impact of deregulation is yet to be measured.

In the two years since the Act was passed, there has already been a considerable change in the character of the industry. The once clear lines of distinction between "trunk," "local service," "commuter" airlines, and even some "air taxis" are becoming increasingly blurred. Patterns of service, route structures and equipment usage are changing in response to conditions in the marketplace for air transportation services. Therein lies a problem!

Where years of specific types of service have become historic -- if not tradition -- a network of supply, storage and distribution of aviation fuels has evolved. Now, with one stroke of the pen, the Act has changed all that by sending various carriers scrambling to provide service in areas where passenger population is more dense. Thus, the sudden shift in the quantity of air transportation being provided leaped years ahead of established fuel supply and distribution networks.

Aviation Fuel Credit Card Purchases

Since aviation fuels were decontrolled in early 1979, the oil company credit card system has undergone dramatic change. The credit card interchange program, a system where oil company credit cards were accepted at FBOs other than those affiliated with the issuing oil company, has, for all practical purposes, collapsed. In addition, some oil companies are assessing service charges or processing fees to their own affiliated retailers.

To exacerbate the credit card situation at the retail consumer distribution level even further, some credit card applicants, especially air taxi operators, are experiencing extreme difficulty in obtaining credit in any form from the major oil companies. Inquiries into the matter have revealed that some air taxi operators are being required to furnish irrevocable letters of credit of extremely high limits in order to receive credit in any amount.

Attracting New Suppliers

The last five years have added new dimensions to the problem. Inflation has remained higher than expected. Fuel costs have soared. Decreased demand for refined products -- especially for motor gasoline -- has paved the way for refinery production cutbacks. On the average, refineries are currently operating at 73.8% of capacity, compared with 84.6% for the same period a year ago.

Because percentages of the crude oil barrel that are refined into various products remain essentially the same -- even when overall production decreases -- motor gasoline acts as a barometer for the production of most other petroleum products, including aviation fuel. So, when motor gasoline demand is up, refinery production capacity must be increased to produce enough gasoline to satisfy that demand. And since the "cut of the barrel" for each product remains the same, the production of other products will also be increased under this scenario. Therefore, the opposite is also true. When the demand for motor gasoline is down, refinery runs are decreased, resulting in decreased production of all products. These same rules do not apply when the demand for aviation gasoline changes!

Limited primary storage facilities also dictate refinery operations. When storage is full and demand is low, refineries are forced to reduce production.

To illustrate this point, current stocks of all motor gasolines are up over 26 million barrels from last year and distillate stocks are up over 24 million barrels for the same period.

Under these conditions, it is extremely difficult, perhaps impossible, to attract new suppliers of aviation fuels -- especially aviation gasoline -- into the market. Such a market entry is feasible only when a new supplier: (1) has access to crude; (2) has operable refinery capacity and available storage; (3) can easily fit aviation fuels into its existing distribution network; and (4) can make an adequate return on its investment.

THE "SUPER FBO" SOLUTION

Some oil companies are restructuring their marketplace by withdrawing from various geographical regions and ending or attempting to end supply agreements with FBOs that have been their historic customers. In other cases, where an oil company intends to remain a dominant force in a given region, it is ending or attempting to end supply agreements with FBOs unable to accept a full tankload of fuel as a minimum delivery.

In those areas where supply for smaller operators is a problem, one possible alternative is for FBOs with sufficient storage or with the financial ability to create new storage, to become "jobbers" for those smaller operations in their vicinity. This is currently happening in several areas of the country -- we call it the "Super FBO" solution.

Strategic Locations

An important consideration for the success of this new generation of jobbers will be their location(s). It could be a self-defeating proposition if numerous "Super FBOs" were crowded into one corner of a geographical region supplying only those nearby locations, while smaller operators scattered throughout the rest of the region did not share the benefit of being collocated near a "Super FBO" site.

In addition to strategic location of these new type jobbers, some anti-trust questions arise well in advance of implementation of such a program. For instance:

1. Who makes the decision "who will be located where?"

2. What happens when a "Super FBO" refuses service to a potential FBO customer?

3. What about the contractual relationship between the "Super FBO" and his FBO customers?

4. How does NATA -- or any organization or company -- act as a clearinghouse in such a scenario?

Storage

Capital formation for such an enterprise must be thoroughly considered regardless of the scope and magnitude of an individual endeavor, especially for those jobbers required to provide additional new storage facilities. Today's construction costs for new underground storage is about $3.50 per gallon of storage. Based on the current rate of inflation, by 1990 that cost is likely to rise to $8.00 per gallon of storage.

Environmental constraints, if any, on underground or above-ground storage would have to be overcome, including compliance with EPA's requirements for "Spill Prevention Control and Countermeasure Plans" (40CFR112).

Local licensing requirements, ordinances and zoning laws dealing with fuel storage would have to be met.

Co-mingling of Fuel

The "Super FBO" or jobber would be moving into a new area of products liability that was previously covered by the oil company.

By today's standards, oil companies are unwilling to participate in contractual relationships involving co-mingling of fuel. The "Super FBO" concept is totally dependent on this roadblock being removed!

And, those of us in this industry are aware of FBOs seeking fuel from markets of new supply. However, airport lease requirements, in many cases, require the FBO to make its purchases from a "major supplier," thereby creating an explicit prohibition on the purchase of fuel from other than historical sources.

Stringent quality control procedures acceptable to the primary supplier would have to be in place to make the co-mingling of fuel feasible and to alleviate the problems described earlier.

Transportation to/from Central Storage

New, specific levels and types of insurance will most likely be required for anyone engaging in over-the-road transportation of aviation fuels to/from central storage depots.

Compliance with certain Interstate Commerce Commission (ICC) rules, as well as local licensing, ordnances and zoning laws will be necessary.

The quality control steps to be taken for the purposes of transporting and delivering aviation fuels will be just as stringent -- perhaps more so -- than they are when fuels are initially co-mingled at the "Super FBO" site.

While capital formation for the purchase and maintenance of a transportation fleet may not be as expensive as additional new storage capacity, it will be nonetheless extremely costly. Today's average cost of a new, over-the-road tanker is $95,000; by 1990 the same unit will likely exceed $120,000.

SUMMARY

Today, NATA has provided some important background information on the problems that are inherent to the supply and distribution of aviation fuels, and has offered one possible solution to the difficulties that are likely to be encountered in the years ahead. However, in doing so, we are now raising some new, and perhaps even more difficult, questions.

In our view, the coalition of knowledge and experience gathered at this conference is well equipped to help us answer these questions.

CRC AND ITS ROLE IN GENERAL AVIATION FUEL

Kurt Strauss
Texaco

This presentation is about a different organization which is more likely to get involved in future research projects than any of the ones that you've heard about until now.

The objectives of the Coordinating Research Council, or CRC as it's commonly known, are:

- Encourage and promote the arts and science by directing scientific cooperatives.

- Research in developing best combinations of fuels, lubricants, and equipment in which they are used.

- To afford the means of cooperation with the government on matters of national interest in this field.

Like all cooperative organizations, the CRC is limited in what its members can do. The CRC can develop research procedures; for example, all the knock-test engines that we have at the current time were developed by CRC as a cooperative endeavor. A number of other tests or procedures have been developed, but they were developed as research procedures, not as standard methods of test. The organization spends a fair amount of time on collecting information; for example, every year there is an extremely large program that establishes the maximum, minimum and average knock-rating of new cars. The key note here is that for any one company to do this work would cost a tremendous amount. By cooperating, that expense is spread out and the entire industry gains in the matter.

CRC works in a number of different ways. It can conduct cooperative studies such as the octane study. In a number of cases, CRC has directly negotiated research contracts with the government. In other cases it has acted in an advisory manner to the government and in still others it is primarily an information gathering or liaison activity.

Very basically, the CRC is a child of two industry groups: the Society of Automotive Engineers (SAE), and American Petroleum Institute (API). There is a board of directors, seven directors being appointed by each of the parents. These are generally senior management people in the oil, automotive, and aviation industries. There are four major committees: an Aviation Committee; the former Motor Committee now called the Light Duty Vehicle Committee because it will include light duty diesels as well as gasoline engine studies; a Heavy Duty Vehicle Committee' and a fourth committee which concerns itself primarily with air pollution.

We're interested mostly in the Aviation Committee which currently has 12 engine and airframe members, four airlines, seven government organizations, 19 fuel, lubricant and additive manufacturers, and one independent laboratory as a member.

The Aviation Committee works through a number of groups which are named after the subject they are studying. These include electrical discharges, aircraft exhaust, oxidation stability, lubricity, combustion and low temperature performance. These groups are primarily oriented to jet fuel because that is where the research activity has been. This is also where the problems had been. Obviously, a lot of these problems carry over to the jets in general aviation.

There are newer groups, and I will call your particular attention to two or three. We're in the process of forming an aviation engine test group. This group has been requested by ASTM to come up with a simpler test than the current aviation gasoline supercharged rating method.

It is felt that the requirement of that particular test is actually a deterrent to manufacture. Not only are there no new rich rating engines being installed, but a number of those that are in place now are being discarded slowly. They are difficult to maintain. They require highly skilled operators, and if CRC can come up with a simpler test (and there are reasons to believe that this can be done), we feel this will be a step in the right direction.

Fuel low temperature flow is a study being carried out by NASA under contract. CRC is advisory on the contract. A particular computer study was done on two long distance business jets to establish the interrelationship between fuel properties and the business jet's ability to go long distances at high altitudes. Because of different configurations and flight speeds, the results differed markedly from large airliners.

The last item being carried out for FAA is an investigation of the properties of fuels with reduced flashpoints, again a subject of interest to general aviation as well as the airlines.

I hope this brief review gives you an idea of what the CRC is and does, so that if we ask you to assist in its work we can count on your cooperation.

GENERAL AVIATION FUEL AND ITS DISTRIBUTION TO THE AIRPORT

Walter V. Paulhus
Texaco

An informal survey of the oil industry as regards aviation gasoline reveals the following pattern of fuel distribution. While there is no predominant method of transportation for the entire industry, it is noted that refinery location and market concentration will dictate if shipment is to be made by ocean tanker/barge/pipeline/transport truck.

1. Ocean Tanker: A common method for all companies to move product from the Gulf Coast and East or West Coast refineries to oil company storage terminals is by use of ocean tankers into company storage.

2. Barge: The method used by oil companies to move product on inland waters; also used in Gulf of Mexico. In most cases, product is moved from refinery to oil company storage.

3. Pipeline: Due to limited amount of avgas sales, only one company surveyed used pipeline as the primary supply source. In all cases, the pipelines were used to move product from refinery to oil company terminal storage.

4. Transport Truck: Generally the most frequent method of moving product to the airport. Transport truck is used direct from refinery to airport if the airport is not too distant.

As a general industry summary, you will find aviation gasoline is transported by ocean tanker/barge/pipeline from refinery to oil company terminal storage. From oil company terminal storage the product is moved by transport truck to the airport storage.

It is noted that, due to the relatively small volume of aviation gasoline sold, a refinery will produce a minimum batch to move on a tanker, barge or pipeline into a market area where this same batch will then be divided into separate terminal storage locations. From these storage locations, transport trucks will supply the numerous small FBO's around the supplying terminal. Due to the small sales, limited storage, and minimum refinery batch production, aviation gasoline is usually not a product that can be purchased on the spot market.

The distribution system becomes even more complicated for aviation gasoline due to the following:

A. Refineries making aviation gasoline are few in number, normally from major oil companies, and predominantly located in the Gulf Coast area. Due to the low volume of aviation gasoline compared to other high volume products, such as motor gasoline, a refiner will make a special run of aviation gasoline which will usually be stored in one segregated tank. This one batch of aviation gasoline may supply a distribution system for several weeks or longer. Since aviation gasoline is manufactured with a very close octane

(rich-rating) specification, the product could go "off-spec" prior to being shipped and result in a critical shortage of product while awaiting another special production run.

B. Since aviation gasoline is moved through the system in very small volumes and only a few days each month, it is impossible to designate ship compartments, barges or transport trucks as segregated only for aviation gasolines. As such, prior to movement of the product, transportation unit compartments must be cleaned. This results in higher costs and increases the possible contamination of product.

C. In storage terminals, the use of vapor recovery systems is now necessary for aviation gasoline. The high cost of these systems cannot be justified by the small volume of aviation gasoline handled and, as such, the smaller volume terminals are being closed to aviation gasoline and the product is being consolidated in a few distribution points, which therefore increases the distribution costs and physical handling problems of the product.

D. Due to the ease of contaminating aviation gasoline at the terminals where it is still handled, a completely segregated system is installed utilizing floating roof storage tanks, separate delivery lines, separate loading rack lines, and filtration system. Again, this special handling of a low volume product is costly.

Reference has been made to aviation gasoline as a low volume product. To put this problem in perspective, you would have to appreciate that in the entire U.S., aviation gasoline sales amount to some 500 million gallons per year. This would represent only one-half of one percent of the motor gasoline sales. It is commonly stated in the industry that yearly evaporation of motor gasoline from storage tanks exceeds total aviation gasoline sales. In a refinery manufacturing and distribution system designed to move tens of billions of gallons, it is very costly and difficult to handle a relatively small volume of aviation gasoline that requires very special handling.

One method developed to help distribute aviation gasoline is the use of product exchanges. This is a method whereby a refinery in one area would produce product for one or more suppliers in that area. In exchange for this production the suppliers would exchange product they made in another area. This method of exchanging product between refineries allows suppliers to supply in markets where they would otherwise not be represented. It also reduces the cost of transportation to bring product into an area as well as reducing the large capital investment that would be required to establish shorage tanks and distribution in exchange areas.

The Aviation Technical Services Committee of the API is working on standardization of nomenclature and specifications that apply to the handling of aviation gasoline. Any efforts that will result in the ability to handle the product easier without loss of quality will benefit the entire aviation industry.

Aviation gasoline supply problems can, and frequently are, complicated due to the limited amount of storage available for aviation gasoline at both refineries and oil company storage areas. Because of the low volume of aviation gasoline sold in comparison to other products, there is often only one storage tank available for aviation gasoline. If for any reason this tank becomes contaminated or a batch of off-specification product reaches the tank, then it is very possible an entire aviation area affecting several states could be without product until the off-specification tank

is cleaned and refilled with good product. There is very little flexibility to the suppliers if the normal aviation gasoline supply system is upset at any point in the system. This inherent danger in the aviation gasoline supply system cannot be easily corrected as there is very limited future aviation gasoline growth projections that would encourage the oil industry to make substantial changes to its existing pattern of manufacture and distribution.

In summary, the following points are stressed.

A. Aviation gasoline is a low volume, quality sensitive product that is manufactured in "special" batches.

B. Aviation gasoline must be distributed in a high cost "segregated" system.

C. Due to the low volume of product moved, it is difficult, due to cost, to design a special aviation gasoline distribution system for the entire country. As such, the aviation gasoline must be handled within the existing multi-product distribution system that is designed to function on frequent movement of high volume products.

It should be noted that while we have confined our remarks to aviation gasoline, we do have aviation jet fuel moving through the same distribution system. However, jet fuel is moved in a much larger quantity, involving a far more flexible and dependable supply system. As such, you in no way incur the same distribution restrictions for aviation jet fuel as you do for aviation gasoline.

THE SPARK-IGNITION AIRCRAFT PISTON ENGINE OF THE FUTURE*

Kenneth J. Stuckas
Teledyne Continental Motors
Aircraft Products Division

INTRODUCTION

With the award of a contract two years ago, NASA gave Teledyne Continental an unique opportunity. This was to design an advanced technology spark-ignition engine on the basis of technological merit without constraints from past practice. The resulting study comprised the whole gamut of technology potentially available for this engine by the year 1990.

Table I is a list that shows the order in which we ranked the advanced technology items in terms of importance. At the top is fuel. An engine cannot be designed until the fuel type is specified. Second is the combustion system. Next is the thermodynamic cycle. Supercharging, turbocompounding and bottoming cycles are modifications that help improve overall engine efficiency. The list concludes with engine operational systems, configurations, cooling, materials, manufacturing, engine auxiliary systems and finally, lubricants. Configuration and cooling are ranked at the same level of importance because they are interconnected. Some engines, because of their configuration, need to be liquid cooled. Materials are included only for weight reduction purposes.

FUEL

Let us begin our discussion by a consideration of future fuel possibilities. Figure 1 shows the present energy use in the United States. All forms of energy totaled 14.78 billion barrels of oil equivalent per year in 1979. About half of that energy came from oil, and half of that was used for transportation. Consequently, about one-fourth of all the energy consumed in the U.S. was by transportation. Motor gasoline comprised 73.3% of that transportation fuel in 1979. Aviation gasoline was only 0.4%. That is about two tablespoons of avgas per gallon of motor gasoline, a small amount.

Figure 2 shows that of all the fuel used by aviation; avgas was 3.5%; the naphtha-type jet fuel, JP-4, was 19.3%; and the kerosene-type jet fuel, Jet A, was 77.2%. The fuel used by General Aviation, including business jets which use Jet A fuel and piston engines which use avgas, was about 7.5% of all fuel used by U.S. aviation.

Figure 3 gives an estimated comparison among several primary energy resources of their conversion efficiencies to useful internal combustion engine fuels. The most efficient process is the conversion of petroleum to gasoline at about 84%. Many people

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*The remarks of Dr. Stuckas were drawn in large part from the more detailed report, "Advanced Technology Spark-Ignition Aircraft Piston Engine Design Study," NASA CR-165162, November, 1980.

have proposed biomass derived fuels, but their conversion efficiency is low. On the other hand, a study of Figure 3 reveals that conversion of oil shale and coal to gasoline are relatively efficient processes.

The United States has 33 times as much ultimate energy in coal, uranium and oil shale as the entire world has ultimate reserves of crude oil. Several problems must be solved before large scale production of internal combustion engine fuel is possible from these sources. These are: technology problems, problems with water availability, and environmental pollution. Figure 3 indicates that the best path for the use of oil shale or coal for transportation is to make syn-crude. If fuels are to be made for transportation, why use coal to produce methanol? Why use coal to produce liquid hydrogen? It just isn't efficient. Fuel from biomass which includes ethanol and methanol has a very low conversion efficiency at best. Some experts say it has a negative energy balance, consuming more fuel than it produces. This is because a lot of fuel energy must be put into any system that is going to produce fuel from biomass. Today the fuel we are producing from biomass, namely ethanol from corn, is made using tractors and other vehicles that burn petroleum fuels.

Now, let us consider fuels for advanced General Aviation spark-ignition engines. There are two reasonable fuel possibilities for such an engine: 1) a wide-cut aviation gasoline with an octane rating not less than the current 100LL, and 2) Jet A or Kerojet fuel.

The development of an advanced, high compression ratio, lean-burn combustion system would allow an improvement in efficiency using 100LL, or a wide-cut, 100 octane fuel.

Development of a direct-injection stratified-charge type of engine would permit the use of widely available commercial jet fuel or a wider-cut version of this fuel that could be developed to improve the vehicle-fuel-refinery system efficiency in conserving crude oil resources.

To accommodate the foregoing two possibilities we proposed two engines in our study. The one which used avgas was termed the moderate risk technology engine, and is viewed as a fallback position for the high risk technology engine, which was of the stratified charge variety. Since the main focus of the study was the high risk technology engine, I shall devote the balance of my presentation to it.

Based on the foregoing fuel/engine picture, let us now consider some of the remaining items in Table I beginning with the combustion system.

COMBUSTION SYSTEM

Figure 4 is a picture of two combustion chambers. The first is the standard production combustion chamber. It employs a hemispherical head, two valves, and two spark plugs per cylinder. It's very efficient, and is currently at 8-1/2:1 compression ratio. Naturally aspirated engines using this chamber can achieve 0.385 brake specific fuel consumption (BSFC). We are proposing an advanced combustion chamber to be used with both advanced technology engines. With the moderate risk engine, the objective is to raise the compression and expansion ratio in order to improve the thermal efficiency, but without increased detonation. This is termed the HTCC, or High Turbulence Combustion Chamber. In the case of the high risk engine, which will be

direct injected with jet fuel, this chamber is designed to control the mixing so that the fuel and air will be appropriately located for spark ignition of a stratified charge.

THERMODYNAMIC CYCLE

Table I indicated consideration of turbocharging, turbocompounding and bottoming cycles. Bottoming cycles are thermodynamic cycles that convert the exhaust energy to work, by means of an auxiliary heat engine. The work is added to that of the crankshaft. That option was found to add too much weight and was rejected. On the other hand, turbocompounding was found attractive. It's not new, but it has never been applied to engines of this size before.

On the left in Figure 5 is a schematic of the turbocharging process as it exists today in aircraft piston engines. The exhaust leaves the engine and enters a free turbine which drives through a common shaft connected to a compressor. This compresses the air which goes into the engine. Turbocharging serves several purposes. First, it provides more power from the same size engine. Second, it provides that power at very high altitudes. And third, it provides a ready means for cabin pressurization. Consider our biggest engine which is rated at 435 horsepower between sea level and 22,500 feet. This engine is turbocharged. However, there is still excess energy in the exhaust which is being discarded. A combination of turbocompounding plus turbocharging can extract additional energy without a significant weight penalty. In turbocompounding, the exhaust leaves the engine and goes through a turbocompounding power turbine and then by some means, gears are shown here, the speed is reduced and the exhaust produced work is routed through a clutch and added to the engine drive shaft. The remaining gases go through a second turbine which is similar to a normal turbocharger turbine except it must be more efficient because there is less exhaust energy available.

In the past we have had turbocharger pressure ratios of 2.77:1 with an adiabatic efficiency of 55% and compressor speeds around 70,000 rpm. Current designs are at a pressure ratio of 3.7:1 and the same adiabatic efficiency, but now compressor speeds are closer to 100,000 rpm. For the turbocompound engine a better turbocharger is needed. We have estimated a 4 to 5.2 pressure ratio with a compressor adiabatic efficiency of 78% and speeds exceeding 100,000 rpm will be required. That is not easy to achieve.

Figure 6 shows a speed reduction unit called the Nasvytis traction drive. Dr. Nasvytis has been working with NASA for some time on this concept. We've chosen this reduction drive for the turbocompounding power turbine instead of a gear set. For high speed reductions, from 100,000 rpm down to 2000 to 3000 rpm, a gear set and this device have comparable mechanical efficiency. (For low reductions of 2:1 or 3:1, gears are clearly more efficient.) The Nasvytis traction drive also has another unique capability. Most traction drives have to be prestressed to a level that will handle the maximum torque output plus some overtorque factor. In this unit, the Hertzian contact stress is proportional to the torque transmitted by the unit. Thus it should have a long life. Quite a bit of testing has been done of the Nasvytis drive and it looks very promising. As a result it has been incorporated into our turbocompounding scheme.

OPERATIONAL SYSTEMS

Both air cooling and liquid cooling were considered. While an absolute comparison is difficult, we determined that for this size engine there is basically no weight advantage to either liquid cooling or air cooling, given equal skill in application of both. And, in fact, there are some distinct disadvantages to liquid cooling. One disadvantage is that given an upper limit to coolant temperature, on a hot day the difference between the radiator temperature and the outside air temperature is small; therefore, the radiator must be large since it must be sized for the worst case condition.

Liquid cooling presents plumbing problems also. These are an added maintenance item. Now, admittedly, aircraft are maintained fairly well for the most part, but the maintenance item would be a big problem compared to air-cooled engines. Another problem is where to put the large radiator, especially in a single engine aircraft. Air must flow through it. Consequently, an aerodynamic drag penalty will result. One idea is to make the radiator integral with the wing skin, and let the surface of the skin cool the liquid. Aerodynamicists claim that this will incur a drag penalty also. In summary, there are penalties associated with liquid cooling that don't exist with air cooling. Consequently, we have chosen air cooling as the best bet also because we know how to design air-cooled engines.

The effect of material substitutions on the outcome of our designs is not well known. We cannot ascribe a dollar value to weight savings with any certainty. The present baseline engine is the TSIO-550. It has eight pounds of miscellaneous materials, 332 pounds of steel, 245 pounds of aluminum, and virtually no advanced materials beyond high-performance alloys which have been used for ten years. Total engine weight is 585 pounds. The high risk technology engine has six pounds of miscellaneous materials, such as rubber and copper. It has only 80 pounds of steel, mostly in the cylinder assemblies, the crankshaft, and the camshaft. This engine has 200 pounds of aluminum and 119 pounds of advanced materials for a total engine weight of 405 pounds, or a 31% weight reduction. These advanced materials include: titanium, carbon, graphite, boron-reinforced plastic, and ceramics. As an example of weight savings, a titanium connecting rod would weigh only 2/3 that of a steel rod for equal strength.

There are some interesting material possibilities for turbocharging and turbocompounding applications. These are alpha-phase silicon carbide ceramics. Two examples are shown in Figure 7. These were made by the Carborundom Company. The big scroll housing is an example of a complex part made from the alpha silicon carbide material. The part shown at the lower left in that Figure is a little turbine rotor from a turbocharger that has actually been run in a Volkswagen engine. These materials weigh about 40% of their metal counterparts. In the turbine rotor case, if the mass of the rotor is reduced, its containment requirements are much less than that of a steel or super alloy rotor. Thus the housing could be made lighter, making the whole turbocharger and turbocompounding assembly much lighter. In our application the peak temperatures are only 1650°F. Since the material has an upper temperature limit of 1850°F, it is not being used to its full capability. As a result there is some built-in safety factor. These materials will be very beneficial if they can be developed in a timely manner for the engine.

Redesign using traditional materials can also save weight. Figure 8 shows two crankshafts. The top one is the current state of the art crankshaft. On the right is a Houdaille viscous damper and three sets of pendulum torsional vibration dampers. These are distributed along the crankshaft. They do not balance the engine, but are there for the purpose of absorbing torsional vibrations. Each set absorbs its own particular mode. This crankshaft weighs 74-1/2 pounds.

Consider the Tiara engine, an advanced design which was in production some years ago. It had a crankshaft which was relatively light resulting from the absence of the dampers. Instead, on the left end was a device termed a V.T.C., or Vibratory Torque Control unit. The V.T.C. unit varied the stiffness of the crankshaft assembly making it either hard or soft, depending on the speed of the engine. The V.T.C. unit effectively eliminated the need for the heavy sets of pendulum dampers for reducing stresses. This crankshaft weighed only 34-1/2 pounds. A system similar to this would be used in the high risk technology engine to reduce weight and lower torsional stresses resulting from higher peak firing pressures. That crankshaft is shown in the lower portion of Figure 8.

Now let us mention advanced technology possibilities for electronically controlled fuel injection and ignition. Electronic engine controls can utlimately provide single lever operation instead of the three controls per engine which are used now: mixture, prop and throttle.

RESULTS

Our design goals as set forth by NASA were modified several times to accommodate new information. The high risk technology engine using a Jet A type fuel met the 250 horsepower criteria for the maximum cruise power. Cruise specific fuel consumption was 0.331, which exceeded the original target of 0.38 by a fair margin. Some of that savings came from the combustion system, but most of it came from recovering the waste exhaust gas energy through turbocompounding.

Now consider specific weight. The engine achieved 1.16 pounds of engine weight per brake horsepower which fell short of the 1.0 pounds sought. Achieving that goal would have added a great deal of additional cost. A 50% cooling drag reduction was sought and a 52% reduction was predicted. The selling price of the airplane compared to existing airplanes was greater. A study was done by Beech Aircraft in which the engine was incorporated into an airplane and a life cycle cost analysis done. Results showed a 6% initial purchase cost penalty, but the life cycle cost was predicted to be 15% less than existing engines because of the fuel economy gain. In addition, it met the former 1980 EPA exhaust emission standards.

Following is a summary of where the energy savings were realized. In a current technology engine 30.5% of the fuel input goes to brake horsepower, 38.9% is lost in the exhaust, and 30.6% is lost to the cooling air. In the high risk technology engine, a fuel input of only 604 horsepower is required to realize 250 horsepower, or 41.4% of the fuel input is realized as useful work. The exhaust energy loss is only 25.8% and the cooling losses are 32.8%. Thus the overall result has been to convert a portion of the exhaust losses to useful work with little change in heat losses.

Figure 9 shows an artist's conception of what the high risk technology engine would look like. The number two cylinder is cut away in order to view the inside. It

is a one-piece unisteel cylinder with cast aluminum cooling fins on the outside. The exhaust system is located on the top with the objective of maximizing pressure pulse recovery for the turbocompounder power turbine. On the left side of the turbocompounder turbine is the Nastytis traction drive, and pads for accessories. This engine has another unique feature. The oil sump is also an oil cooler.

Figure 10 shows a typical twin-engine installation, in which the cooling air comes in the bottom, goes up, and out the back.

Figure 11 shows an overall comparison between three planes with baseline, moderate risk, and high risk engines. For comparison a measure termed "transportation efficiency," is used. This has been normalized to a value 1.0 for the standard baseline engine. "Transportation efficiency" indicates how much fuel will be consumed to carry a one-ton payload a given distance. Results indicate that the high risk technology engine in a single-engine airplane improves transportation efficiency by 63% over the baseline. That's very significant. For the twin-engine installation, that improvement is 68% (see Figure 12). This is a big payoff, even neglecting the fact that airframes can still be improved.

PROGRAM

The program we have defined for developing these concepts into a working production aircraft is a joint NASA and industry program. At first we are looking to NASA to help get the required advanced technology to the point where it can be used. Some programs have started. After mid-1984, the industry will take the technology as it develops and apply it to an advanced engine. The first production airplane is projected for January 1, 1990. Table 2 shows the timetable.

NASA's help is needed in developing this stratified charge combustion system, electronically controlled ignition system, and high efficiency, high pressure-ratio, light-weight turbochargers. Some turbocharger work is underway already. The turbocompounder power turbine reduction drive clutch and control system require development. Much of the fuel savings is coming from turbocompounding, so this is a key area. Also, work on single-lever power control is needed. These are items that we are asking NASA for help in developing so this high risk technology engine can be in production in the next decade.

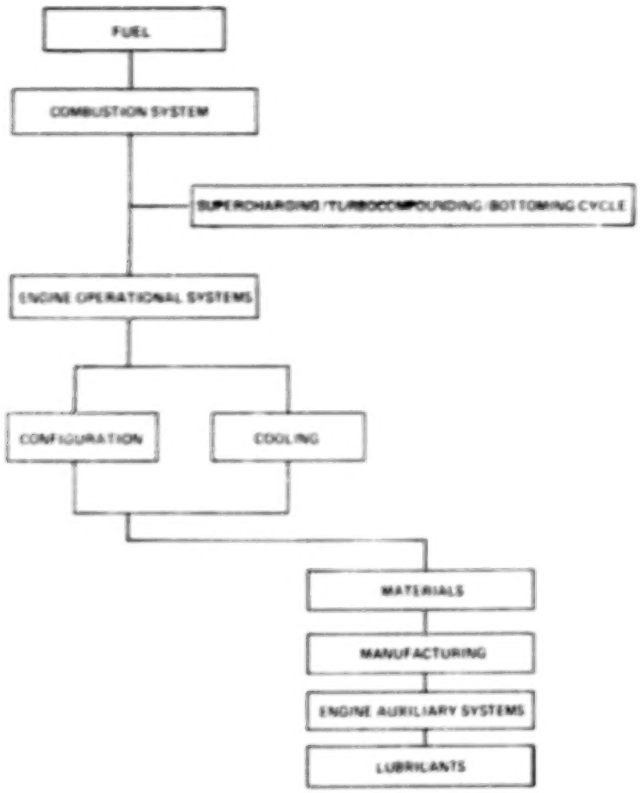


Table 1. - Advanced technology base hierarchical structure

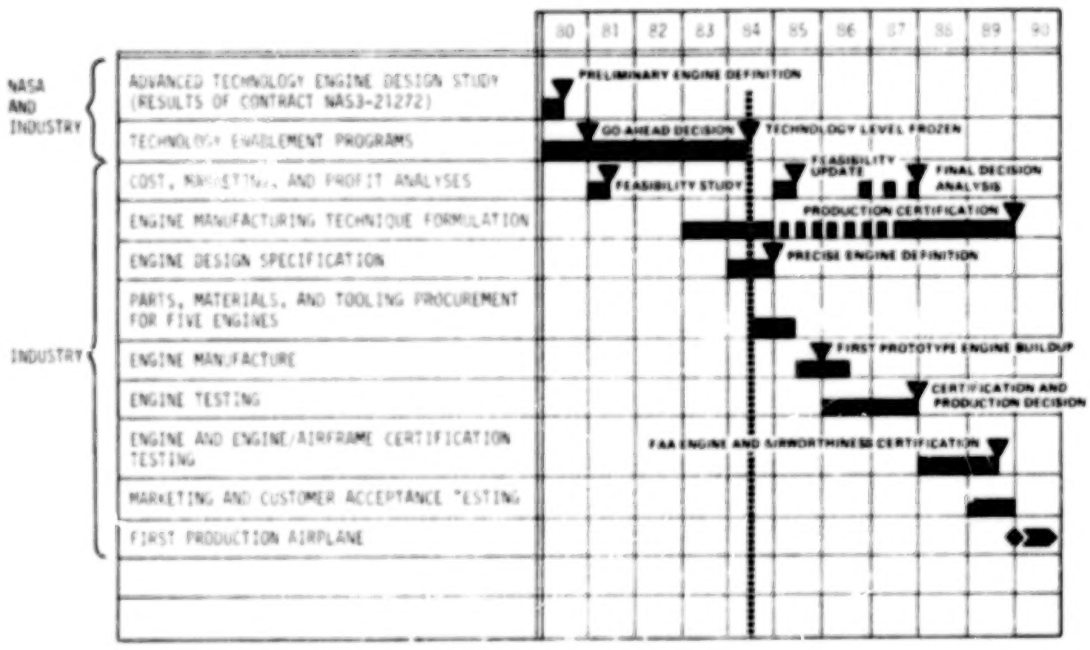


Table 2. - Advanced technology spark-ignition aircraft piston engine program plan

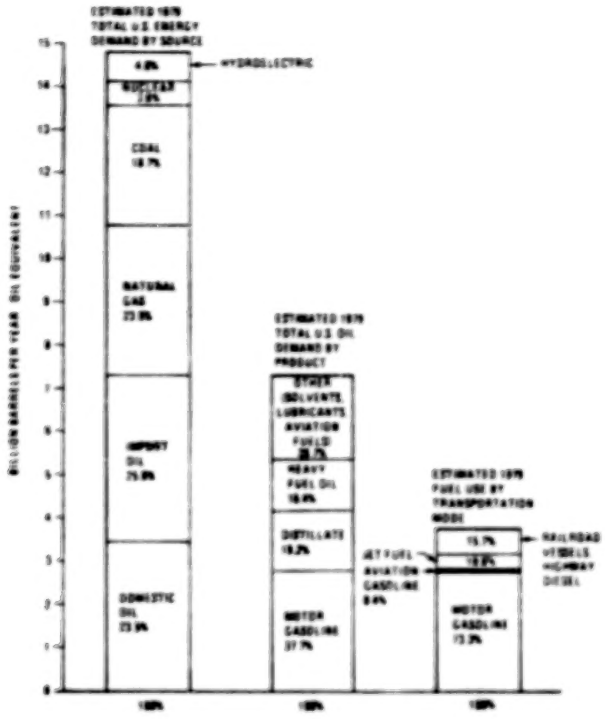


Figure 1. - Estimated 1979 U.S. energy use

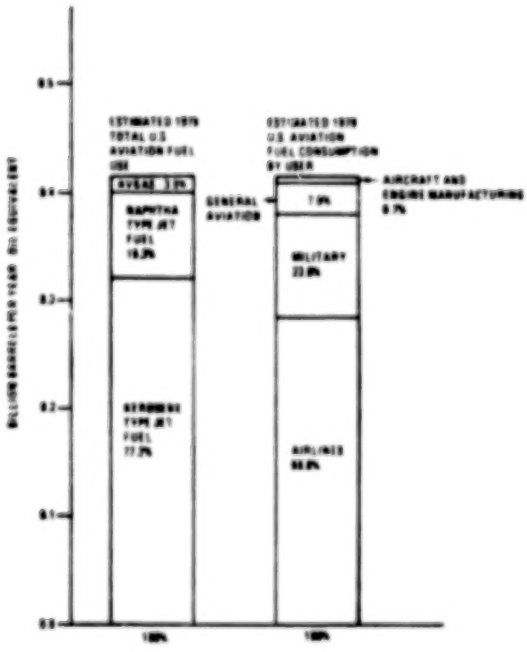


Figure 2. - Estimated 1979 U.S. aviation fuel use

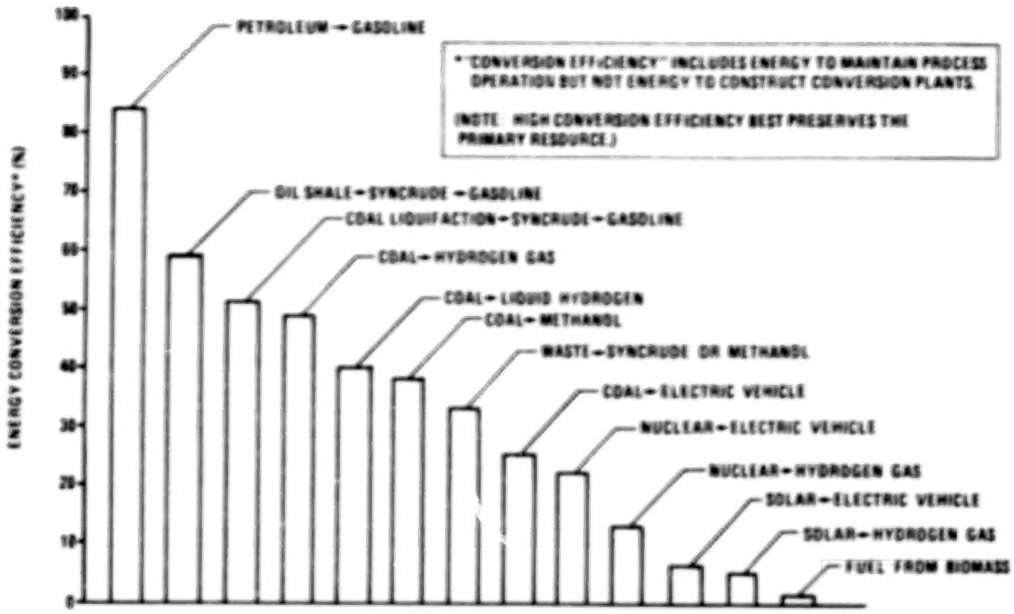


Figure 3. - Estimated conversion efficiencies of internal combustion fuels from primary resources

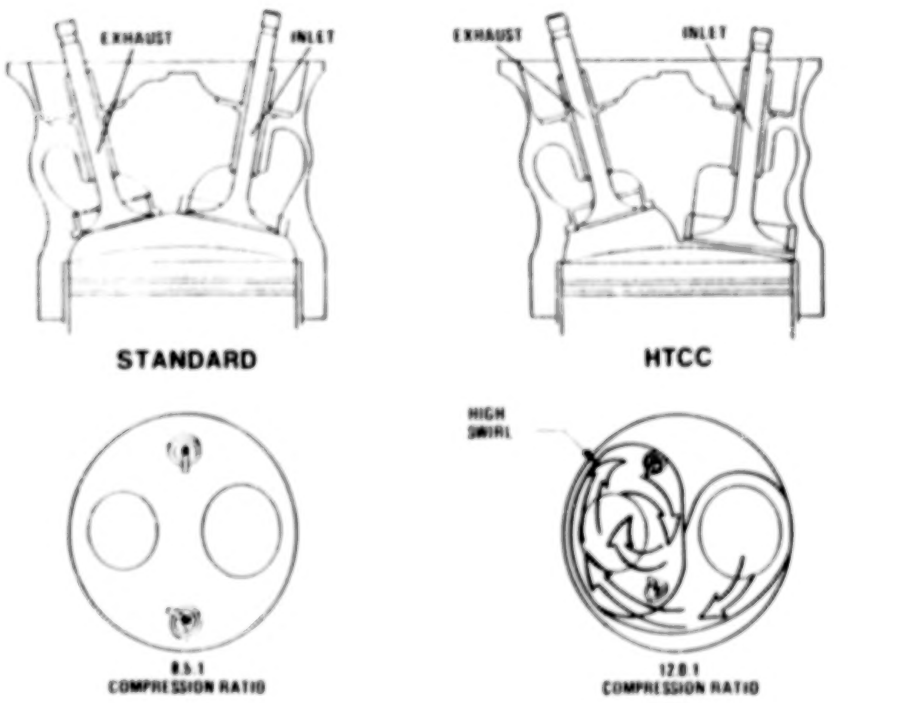
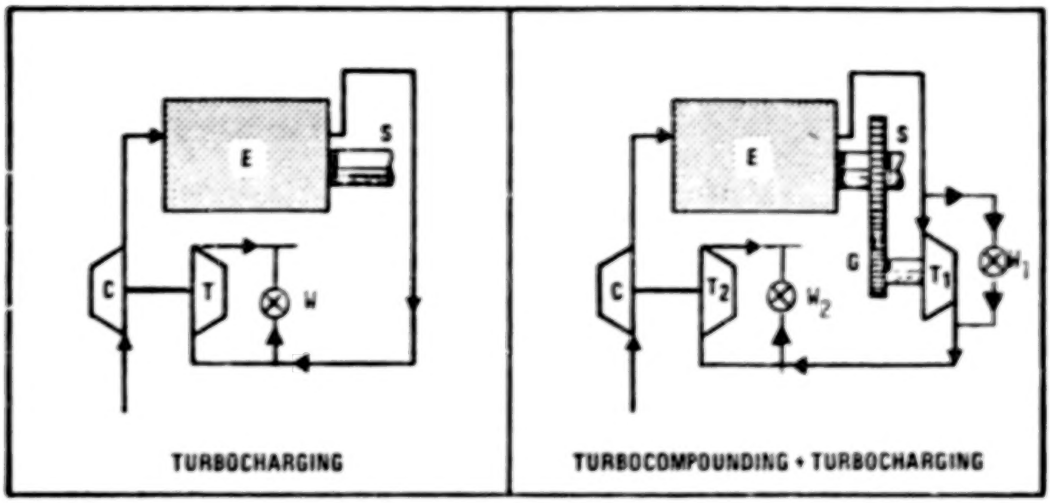


Figure 4. - Comparison between standard hemispherical and high turbulence combustion chambers



E - engine
S - propeller shaft
T, T_2 - turbocharger turbines
W, W_1, W_2 - waste gates
C - turbocharger compressor
T_1 - turbocompounding power turbine
G - speed reduction drive

Figure 5. - Schematic comparison between a normal turbocharged engine and a turbo-compounded engine

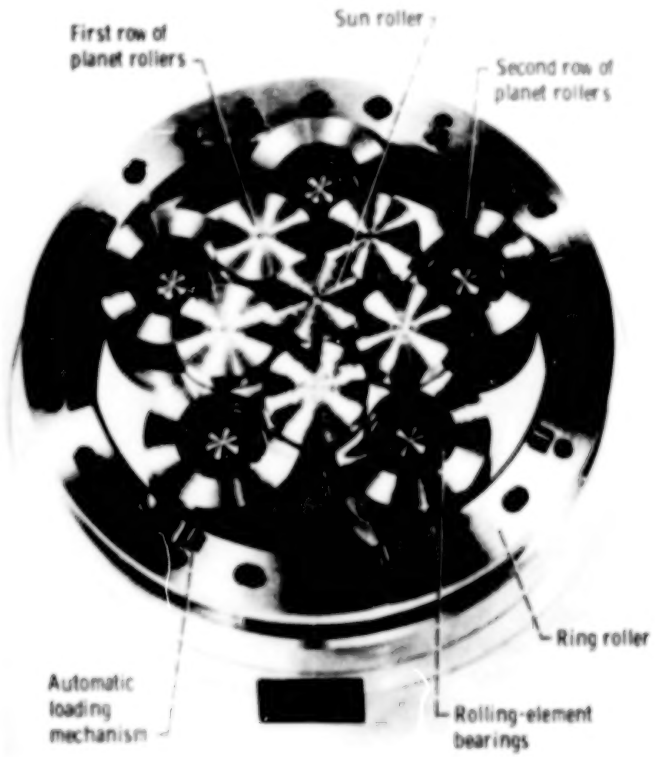


Figure 6. - Basic geometry of a Nasvytis multiroller traction drive

Figure 7. - Alpha silicon carbide turbine wheel and scroll housing

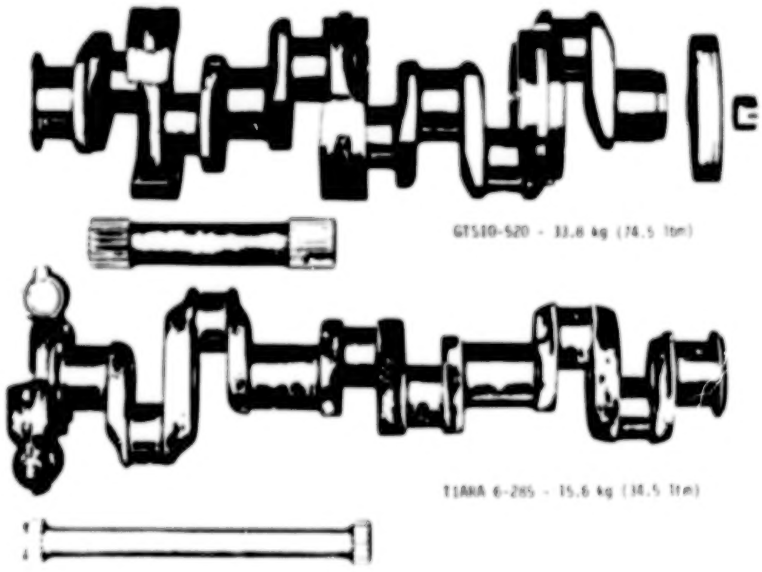


Figure 8. - Comparison of GTSIO-520 and TIARA G-285 crankshafts

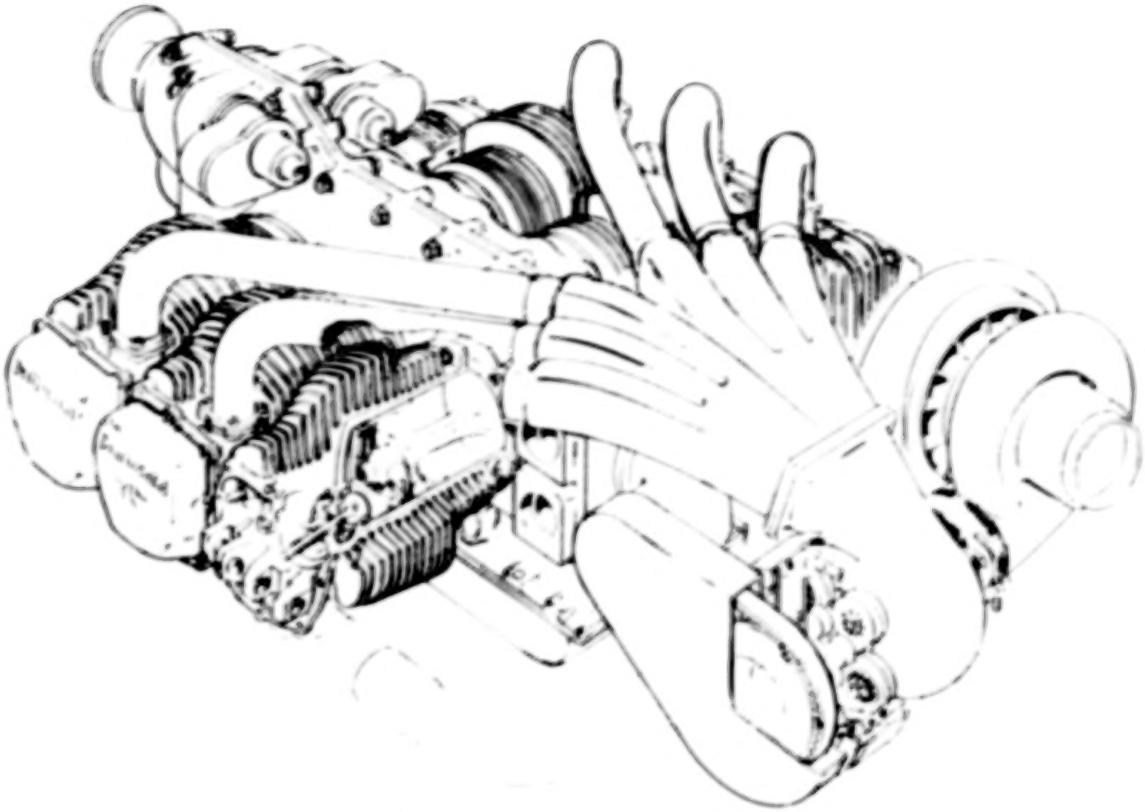


Figure 9. - Artist's conception of high risk technology engine

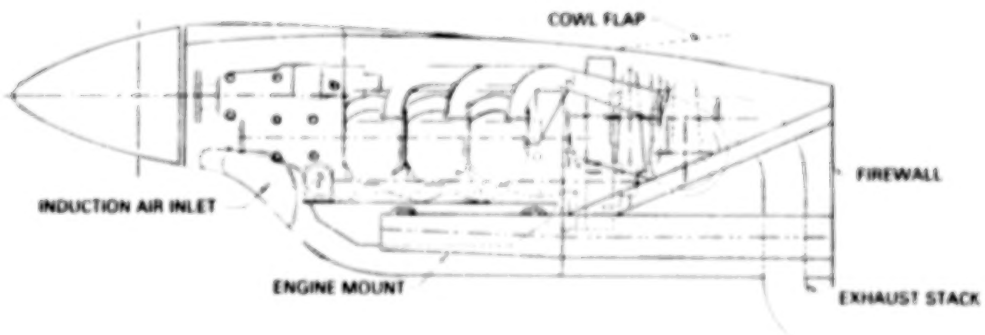


Figure 10. - Engine/airframe integration -- twin-engine installation

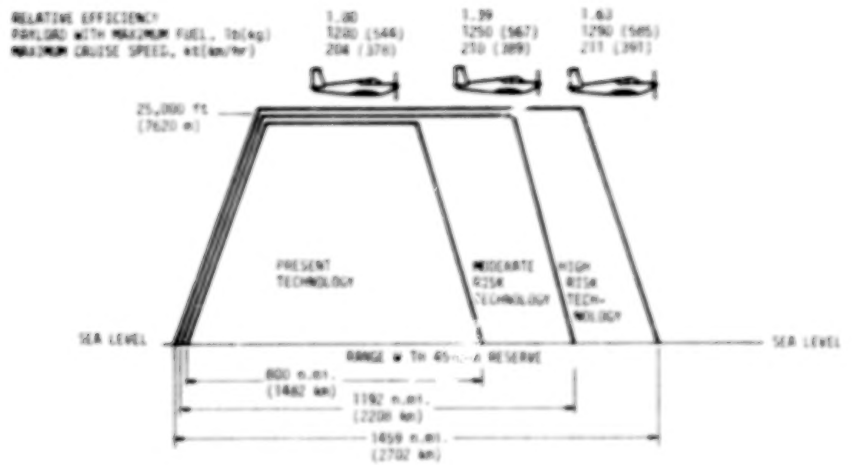


Figure 11. - Comparison of single-engine airplane performance with current moderate risk and high risk technology engines

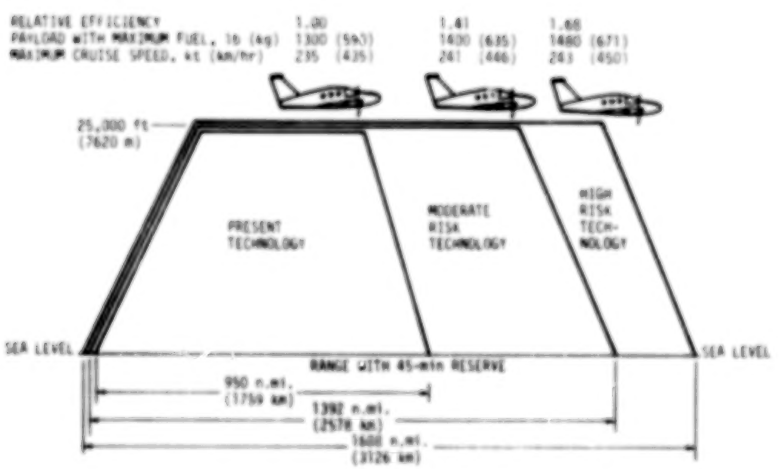


Figure 12. - Comparison of twin-engine airplane performance with current moderate risk and high risk technology engines

AIRFRAME AND ENGINE INTEGRATION, AND POTENTIAL IMPROVEMENTS

David R. Ellis
Cessna Aircraft

This is basically a fuels and engine conference, but eventually those two get joined in an airplane, so it's appropriate to consider the interface here. There are three particular things I would like to talk about. The first was a direct request from Don Patterson: Is there anything we can do with the airframe to cope with degraded engine performance, i.e., lower power or increased fuel consumption resulting from changes in fuels? This led me in my thinking to the general topic of flying more efficiently, and from there into the idea of taking advantage of new powerplants from an airframe standpoint.

This first subject, unfortunately, is a little more real than we like to think. Those of you who are intimately involved in aviation are aware of a detonation problem over the past year with our top-of-the-line single, the Cessna 210. The resulting airworthiness directive action has brought about some performance degradation for the operator through restrictive leaning schedules and restrictions on manifold pressure. Fortunately, in this case we have been able to make changes which will restore performance.

In more serious cases, depending on the level of performance degradation, certain models might have to be dropped if the fixes are either not technically feasible or too costly. The next level of solution in the case of a serious performance loss is probably to recertificate the airplane at a lower weight. A serious power loss is going to affect takeoff and climb performance, and certain of our airplanes are right at those limits and couldn't stand any significant power degradation at present gross weights. This is unfortunate, of course, since it would decrease utility of the airplane. It would also leave an airplane which is overstrength for its gross weight and therefore more costly and less structurally efficient than it should be.

Solutions of a little more drastic nature, but which I would still call near-term, might be a thorough drag cleanup of the airplane in the style that the people at Mooney have done very successfully. This sort of power degradation problem would certainly lead in that direction in order to recover cruising speed in particular. Longer term solutions would be the redesign of major components. We could get our payload back by going to large scale use of composites for lighter structures, or we might get other aspects of performance back by wing redesign. For example, this might be accomplished by combining wing redesign with the structural advantages of the composites and using advanced airfoils of the natural laminar flow type. A complete redesign of the engine installation for lower cooling drag would be another example.

At this point people usually ask why we don't start now to put a longer span wing or some winglets into our designs and begin to fly more efficiently? Unfortunately, those particular solutions are of the sort which work only in the low speed regimes which we do not commonly emphasize in our airplanes now as we are offering a time-saving mode of transportation. This leads me into the subject of the general problems of flying efficiently.

The best fuel efficiency is obtained at maximum lift to drag ratio. The speed at which $(L/D)_{max}$ occurs is a very low speed, somewhere down in the range of normal climb speed. It's far away from normal cruising speed and far away from our normal advertised 75% or 80% power settings. In fact, if we were to build an airplane with a powerplant sized to fly at the most efficient speed, it would immediately be judged as grossly underpowered. When we get enough installed power in the airplane to satisfy us from the takeoff and climb standpoint, we give the customer the opportunity to cruise inefficiently, and, in effect, waste fuel.

Let's digress here and ask the question whether or not we can be more efficient by flying at high altitudes (Figure 1). This helps from the speed standpoint because the true airspeed for given power goes up. However, the absolute aerodynamic efficiency of the airplane doesn't change. The factor $(L/D)_{max}$ is independent of altitude. From an aerodynamic standpoint, and depending on the pecularities of the powerplant installation, the efficiency of the airplane usually doesn't change with altitude. This is true even if we put a turbo-supercharger on it and fly as high as possible.

Figure 2 illustrates the altitude characteristics of one of the industry's most efficient airplanes, the Mooney 231, which gets about 20 miles per gallon. But that fuel efficiency is fairly invariant with altitude between sea level and 24,000 feet. In general, we can say that the capability to fly high gives us more flexibility which we can use to advantage in flight planning to maximize our <u>ground</u> miles per gallon. But it isn't the total answer to efficient flight.

So the question remains, if we're going to waste some fuel in order to go fast, is there an optimum way to do it? It turns out that there is. (See Figure 3.) The least increase in fuel used per unit increase in speed above that for $(L/D)_{max}$ occurs for a speed we'll call V*, which is $V^{3/4} \times V_{(L/D)_{max}}$. This speed is 32% higher than that for $(L/D)_{max}$, and it results in burning 16% more fuel but yields a 24% reduction in flight time. This V* is about 15% slower than we normally fly.

Figure 4 is a plot of speed for best cruise efficiency compared with 75% power cruise speed which is what we usually advertise. We see, for the most part, that all of the airplanes represented by the data points fall below the 100% correlations line at a level which indicates that this "normal" cruise is about 15% higher than the speed for best cruise efficiency.

If you examine the graph closely, the airplanes which are on the lower left of the scale are the smaller, higher drag airplanes with fixed landing gear and single engines (FGSE). In the middle there is a scattering of points which represents retractable gear singles (RGSE) and some of those do get over the 100% line. The latter usually represent turbocharged airplanes which are flying at high altitudes at a 75% power cruise. They are more efficient than most other airplanes. The points at the top are the multi-engine retractable gear (RGME) airplanes which are usually turbocharged and fly at high altitudes.

This leads to a quantity which we can call "cruise efficiency" (Figure 5), which is related to the drag; to zero lift drag and to induced drag. It is a number between zero and one. This chart shows the coefficient "A" which is related to zero lift drag and the coefficient "B" which is related to induced drag, plotted on a carpet plot. In the middle of the plot is displayed the best cruise speed, V*, and the cruise efficiency itself which starts on the upper corner at a value of 0.2, and ends on the lower with a maximum value of 1.0.

The airplane data of the previous chart (Figure 6) are plotted here with an overlay of pure aerodynamic efficiency, L/D. From this, relative cruise efficiency is seen. The multi-engine retractable gear airplanes are to the lower right, displaying values in the neighborhood of 0.6 cruise efficiency; the fixed gear strut braced singles are on the upper left side with efficiencies in the neighborhood of 0.2. The background for this is all very nicely spelled out in a recent AIAA paper, AD-1847, by Professor Carson of the U.S. Naval Academy. This concept of cruise efficiency is nice on two counts. First, it provides some justification for flying an airplane at other than 75% power, but not at 45% power, or whatever low setting it takes to get $(L/D)_{max}$. And second, it can help in the design of airplanes for best efficiency.

This leads to the final topic: How do we take advantage of the new engines which have been discussed by the previous speakers? If we get a new engine, the first temptation is to put it in an existing airframe. Judging by some of the studies that we have seen, this could result in significant weight and fuel savings. Figure 6 shows one example wherein an airframe powered by an advanced rotary combustion engine, which we've been studying under NASA and Curtiss Wright sponsorship, is compared with the same airplane powered by a current generation horizontally opposed air-cooled reciprocating engine. The starting point is a baseline airplane weighing 4000 pounds, with a prescribed mission requiring 440 pounds of fuel. With the new engine the weight comes down significantly to 3890 pounds, and the mission fuel drops by 29% to 314 pounds.

However, the best approach with the new engine is to redesign the airframe to take best advantage of the lower weight and smaller size. We have been studying this too. If you start with a lower weight engine, gross weight is lower initially. If the engine has better specific fuel consumption, less fuel has to be carried. Using that as a starting point, you determine how much the wing size can be reduced. Wing size is the primary change because the people-carrying capsule can't change very much in size unless we develop some way to carry people other than have them sit in chairs. So it's mainly a wing resizing, though it may be possible to reduce tail size at the same time. At any rate, it is a synergistic, interactive process which cycles several times because reducing wing size causes the wing to become lighter and have less drag, thus requiring less fuel capacity, and so on.

Figure 7 shows an example. In this exercise, a six-place single engine airplane is sized to a particular payload and range requirement, namely 1200 pounds (six people and baggage) and 700 nautical miles. This figure represents a baseline airplane to which we compare others; and it utilizes a current generation, although not yet available, engine, the TCM TSIO 550 of 350 horsepower. The axis on the left is gross weight. The carpet plot in Figure 7 shows variations in wing area from 140 up to 220 square feet. The other side relates to wing geometry with aspect ratio (ratio of span to mean chord) ranging from seven on the right, to eleven at the top. The lines in the middle are other constraints which we have placed on the problem.

There is a stall speed constraint of 61 knots. This is the lower line running across the graph. Airplanes above that line are permissible, that is, they will meet that constraint. Those below will not. Likewise, the second line running from the left to the right is the rate of climb at altitude, which assures us that the airplane will be capable of climbing at least 500 feet per minute at 25,000 feet. Takeoff distance may be specified as well as a cruise speed requirement; here $\leq$2500 feet and 210 knots.

The net result is an area of the plot which represents permissible airplanes which meet all constraints. The black point in the middle is the chosen airplane in this

case, and is the lowest weight (4425 lbm) airplane which would meet all requirements. This plane has the smallest size and is least costly. It would have a cruise efficiency of about 0.6, which is very good by today's standards.

What would happen with the same ground rules if we take one of the advanced technology engines and go through the same process? Figure 8 shows the result, wherein a lower weight airplane can be picked because of the much lighter rotary engine and smaller fuel requirement. Most of the performance constraints don't show up on this chart. The airplane climbs much better than 500 feet per minute at 25,000 feet, and it goes much faster than 210 knots. The only requirement that is constraining here is the 61 knot stall speed limit. We are free to choose any airplane above that line. The dark point over on the middle left represents our chosen airplane which weighs 3850 pounds. Compared to the 4425 pound baseline, this is a significantly smaller airframe.

Why did we pick the 3850-pound instead of the minimum-weight airplane at roughly 3650 pounds? The 3650-pound airplane would have an aspect ratio of 5-1/2, and although you could meet the max cruise case with this low aspect ratio, it would not favor efficient flight at low power settings. Although one may be tempted to pick such a lightweight low aerodynamically efficient airplane, we have opted to improve on the cruise efficiency of the basic airplane to a value of about 0.66, and this results in the choice shown.

In conclusion, although we can make up for some engine performance degradation by working aerodynamics to best advantage, the gains there are bound to be relatively small. Nonetheless, they should be pursued. The big gains will come with powerplant advances as they have throughout the history of aviation.

SYMBOLS

Symbol	Definition
A	$\rho f/2w$, sec^2/ft^2
b	span, ft
B	$2W/\rho b^2 \pi e$, ft^2/sec^2
c	cruise condition
C	cruise efficiency = $0.000115(A^3B)^{-1/4}$
D	drag force, lbf
D/L	drag to lift ratio = $AV^2 + B/V^2$
e	Oswald efficiency factor
f	equivalent flat plate area, ft^2
FG	fixed landing gear
L	lift force, lbf
ME	multiple engine aircraft
nm	nautical miles
nmpg	fuel economy, nautical miles/gal
P	power, horsepower
RG	retractable landing gear
SE	single engine aircraft
V	velocity, nautical miles/hr (kt)
V*	velocity for best cruise efficiency = $V^{3/4} \times V_{(L/D)_{max}}$, kt
V_0	velocity at baseline condition, kt
W	weight, lbm

GREEK LETTER SYMBOLS

Symbol	Definition
ρ	density, $slugs/ft^3$
ρ_0	density at baseline condition, $slugs/ft^3$
σ	density ratio, ρ/ρ_0

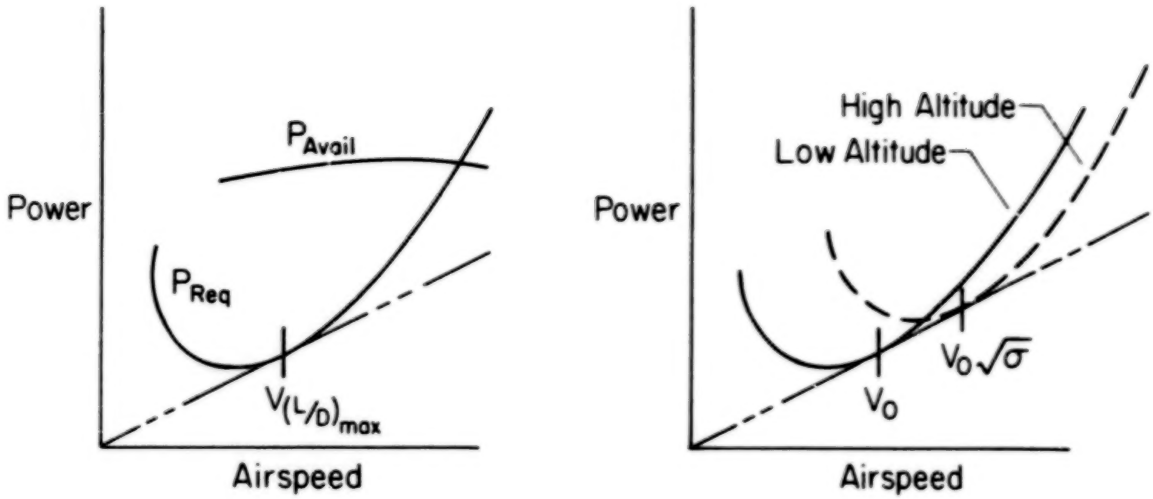
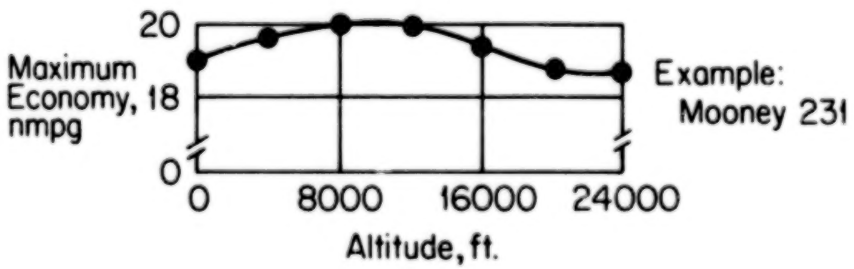


Figure 1. - Power versus velocity for an aircraft at two altitudes. $V_{(L/D)_{max}}$ is most efficient cruise speed.

Flying High vs Flying Low

- Higher true airspeed for given power
- No gain in $(L/D)_{max}$ or fuel efficiency with altitude



- Time spent climbing at low speed
- More operational flexibility with turbocharging
- At maximum operating altitude, speeds are closer to $V_{(L/D)_{max}}$

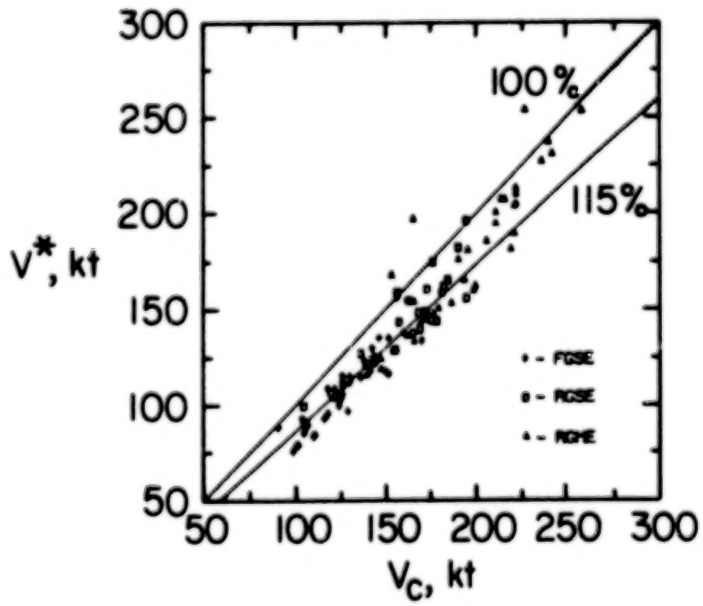
Figure 2. - Characteristics of flying high versus flying low.

Least Increase in Fuel Used
per
Unit Increase in Speed Above That for $(L/D)_{max}$
Occurs for

$$V = \sqrt[4]{3}\, V_{(L/D)_{max}}$$

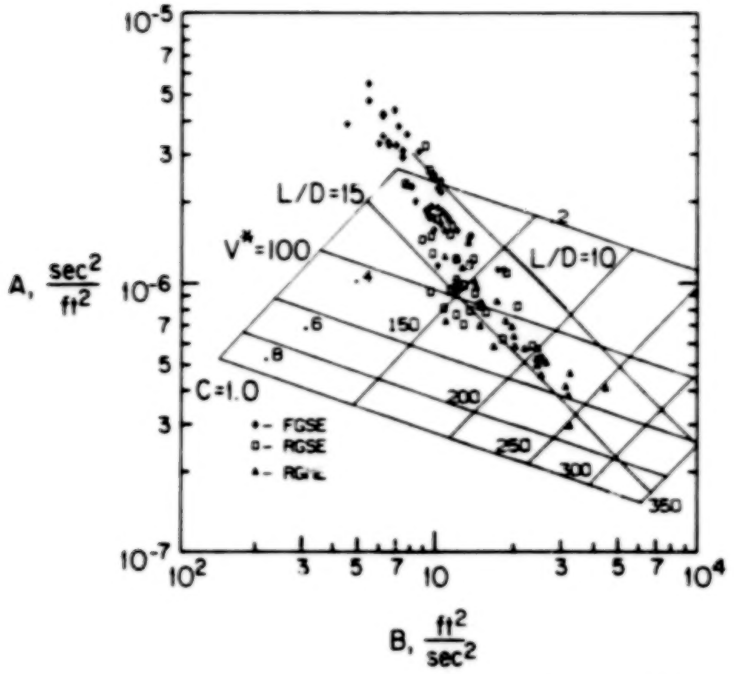
- 32% Increase in Speed
- 16% Increase in Fuel Used
- 24% Reduction in Flight Time

Figure 3. - Most economical speed for flying fast.



FROM: *Fuel Efficiency of Small Aircraft*
by B. H. Carson, AIAA Paper 80-1847

Figure 4. - Most efficient cruise airspeed, V*, versus normal 75% power airspeed, V_C, 111 piston aircraft. Percent lines indicate level of correlation.



FROM: *Fuel Efficiency of Small Aircraft* by B. H. Carson, AIAA Paper 80-1847

Figure 5. - Plot of parameters A and B, 111 piston aircraft. Overlay grid is most efficient airspeed versus cruise efficiency, C. Shown also are two lines of $(L/D)_{max}$.

Old Airframes

Large Weight and Fuel Savings Possible

Example: (Same airframe; engine change only

	Gross Wt, lb.	Mission Fuel, lb. (715 nm Cruise, 20,000 ft)
Current Recip BSFC = 0.45	4000	440
Advanced Rotary Combustion Engine BSFC = 0.398	3898	314

New Airframes

"Resized" for Minimum Size, Weight

Smaller engines, higher cruising altitudes often possible with given constraints

61-knot stalling speed often constrains wing loading and hence cruise performance

Lightweight could allow selection of less efficient airframe.

Figure 6. - Gains in weight and mission fuel from new engines.

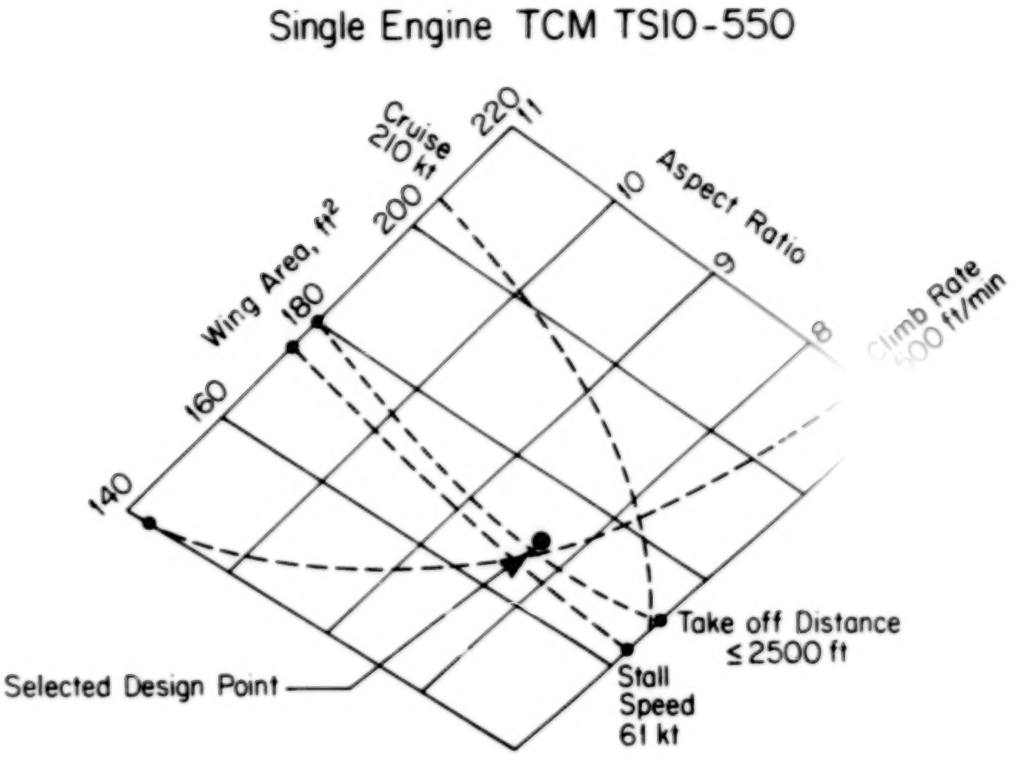


Figure 7. - Baseline conventional piston engine airplane design map. Payload 1200 lbm, range 700 nautical miles.

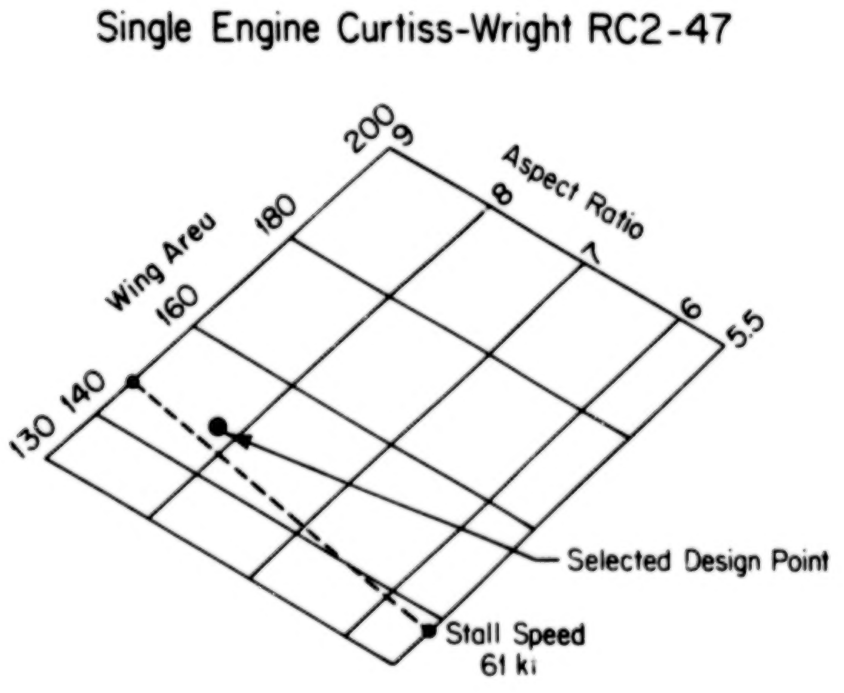


Figure 8. - Advanced technology (rotary) engine airplane design map. Payload 1200 lbm, range 700 nautical miles.

CURRENT DESIGNS, FUTURE POSSIBILITIES, AND PROGRAMMATIC SUGGESTIONS

Larry C. Duke
AVCO Lycoming, Williamsport Division

When one is asked to define the technology required to improve general aviation piston engines, several areas immediately come to mind.

First is the current design engine. With only one class of engine in extensive active production, i.e., the air-cooled gasoline spark-ignition model, the shortcomings of the aircraft piston engine are readily apparent. Next, knowing what is in production now, one tries to envision a new concept engine that will overcome all the limitations of the current engines, and, in fact, does everything from use no fuel to have infinite range of operation. We can go on and on listing the "wants," but at some time we must face which desires are real and which are just that--desires. Finally, how do we proceed from where the technology stands today to that required for the engines needed for the 1990's and beyond?

My remarks which follow are limited to these three areas: current engines, future engines, and the approach to develop them. I plan to touch on technology requirements, but it is my opinion that defining the requirements is not easy. These are the objectives of appropriate studies given the right amount of input. What we need is the input.

To go back to the beginning, let's talk about today's aircraft piston engine. The majority of those currently available are the type now produced by AVCO Lycoming and Teledyne Continental. In the world of internal combustion engines, these powerplants are mature developments for their specific duty cycles. With dependable high-power output, long service life, and low-unit weight as a few of their design parameters, these engines are the cornerstone of the general aviation marketplace. Although their main asset has been and always will be the safe development of power, new challenges make their continued miserly usage of fuel an ever increasing consideration.

However, these concerns are the everyday actions and transactions of the general aviation business. Why, you might ask, is so much being said now? The point is that the fuel situation for the general aviation piston market is becoming worse as time passes. Much has been made of the fact that GA uses less than 0.5% of the gasoline produced. This leads to the position that the aircraft piston engine's requirement to be fueled by a specialized gasoline makes it an obvious target for fuel shortages, price increases or both.

Also due to the structure of the facilities capable for producing aviation grade gasolines, the shortage problem is most critical in countries outside the United States. In fact, from investigations of the aviation gasoline situation, it doesn't take long to realize that several important, although somewhat conflicting, points exist. These can be best summarized as:

1. Petroleum products--as we know them today--will probably be available until the year 2000.

2. The price of avgas is expected to increase and shortage of the product will become more frequent.

3. The shortage of aviation gasoline is not due to shortage of crude oil. Distribution--from refinery to end use--contributes a major impact into avgas cost and availability. Liability concerns tend to cap the fuel specifications where they are today. These apply to the United States market.

4. More critical situations exist now outside the United States.

In shaping the avgas situation to future requirements, there are three paths that could be followed.

Starting with the energy situation as it is now understood, one path could be to make no change at all. This would mean providing the same package--both engine and airframe--to use fuel at "status quo" efficiencies. This approach has large appeal for some production-oriented factions but becomes the target of criticism as an attitude which lacks foresight. The technology requirements for this effort appear nearly non-existent. One might say that only the minute day-to-day incorporations of developments that have been used elsewhere will find their way into engines and airframes of this class. However, these statements are too presumptuous. Consider these facts:

1. If the new technology engine concept were available today, the time to carry the engine through complete development through certification and into initial production is five years.

2. The standard life of today's piston engine is on the order of 15 to 20 years, and it is not expected that newer products would intentionally be designed with a shorter life span.

3. To summarize, if we start developing a new engine today, present fuel, either today's or an acceptable substitute, will still be required in the year 2000. Admittedly, the quantities of the avgas 100 octane requirement engines will be decreasing over those 15 years, but they will still be there, and they will still need fuel.

Remember that the above is based on the presumption that the new technology engine is on the shelf now. Certainly some of the newer developments such as stratified charge, etc., have not been proved to the point of the reliability required for aircraft use. The technology of "no change" is embodied in an unlimited supply of avgas.

The second path to follow stresses more efficient utilization of the energy available today, but still keeping within the structures and limitations of the current fuel and materials. This is within the confines of the engine with its avgas 100 octane requirement, spark-ignition combustion process, and air-cooling system. Essentially, the powerplant would be unchanged from its present basic design concept. The main thrust of effort on this path is to make the entire aircraft more efficient, and the words <u>entire aircraft</u> must be emphasized.

It is within this entire vehicle concept that mid-range gains can be made. Perhaps the best example of this effort can be made by reviewing the recent work of the automotive industry to reduce gasoline consumption. In that industry, significant gains have been made from the dismal 10-12 mile per gallon automobile to the 20-30 mpg vehicles being advertised today.

But where were the gains made? Certainly some improvements were a result of better engine efficiency, by perhaps several percentage points. But the major gains by far have been achieved by lightweight vehicles and better engine-to-vehicle matching. Smaller engines with manual four or five speed, or automatic/overdrive transmissions are now commonplace. The point is better matching of the vehicle to its duty cycle.

We can follow in the tracks of our automotive counterparts by continued fine tuning of the aircraft package. Take, for example, the engine itself installed in a twin-engine aircraft. Current regulations require that in addition to the engine being certified to preclude detonation and so on from a production point of view, it must also cool adequately during single-engine, best-climb operation. This requirement usually means a richer than necessary fuel schedule. The aircraft is saddled with this rich fuel schedule for any operation, even during twin-engine operation when the engine does not demand optimum cooling. The design requirement penalizes the normal operation of the aircraft, and consequently wastes fuel.

I am not advocating engines suitable for normal operation only, but rather the development of flexibility into the engines and aircraft to allow specific accommodation to each required condition for maximum energy efficiency. Further, tailoring of the engine operation to conditions corresponding to climb, airport pattern, and approach can be likewise optimized. In fact, with today's technology and common practices, all operating conditions except cruise offer some degree of benefit from energy management. At cruise the pilot usually has the time and the facilities to lean the engine for best economy according to his situation.

Thus far the main target has been the engine, and a fair amount of gain can be obtained by specific controls on various engine parameters. Usually some form of electronics comes to mind. And this is not unrealistic. Fuel, turbocharger and ignition system monitors are well within technological reach. Usually cost, complexity, and reliability are the barriers to their usage. Only reliability is in need of technological help. Cost and complexity are actually left to the product designer; his requirements and refinements define these parameters.

Alternate lightweight materials may be incorporated for improving the efficiency of the GA piston engine. Some projections have been made that include various new materials in the engine design. The use of titanium alloys and/or composite materials have been proposed as answers to material strength and weight questions. However, cost and usableness play an important role in the adaptation of these materials. For example, at the present level of technology, the use of composite materials is largely limited to flat, sheet-like applications. There are some uses in engine component systems, but the assurance of fiber orientation in a complex casting has not been mastered. Non-destructive testing for quality assurance is still open. Also the attaching technique is often so complex that the additional necessary hardware negates the usefulness of the alternate material. Certainly the development of technology in alternate materials can benefit by advancement in these areas.

Designing to adapt engines to their specific duty cycle may sound as though this is more production- than technology-oriented. However, the concept being addressed is

one of first defining the requirements of the duty cycle, and secondly designing the system to match. Intrinsic to this design process are the tools required. Tools such as heat transfer analyses, finite element stress determinations, and weight/strength correlations in complex parts are some specific examples.

Since I represent an engine manufacturer, I am not qualified to speak in detail about the technology required for aircraft components. That topic is covered in another paper. However, lest we forget, the key to fuel efficiency for the near future, for at least the next five to ten years, will be in making the aircraft package as an entity most efficient, employing already developed technology. Drag reduction, lightweight materials and new propeller design practices can have a significant impact on our fuel efficiency.

Moving on to the technological requirements of the third step in the process, the alternate fuel, several questions need to be answered before charging off on a large-scale program. The most fundamental of these is simple: which fuel? Several alternate fuels have been promoted to replace the current aviation gasoline. Automotive gasoline, alcohols, diesel and turbine fuels each have their strong points as the future general aviation fuel. Several studies have been conducted to provide an answer to this question. If I try to summarize these studies, it appears that a form of turbine fuel receives most of the attention. This is rightfully so because of two very practical reasons--specifications and distribution. The use of an unspecified fuel can lead to the untenable position of an available energy source but no compatible engine or aircraft. Some guidelines must be established and universally accommodated. As mentioned, distribution of the product is a major factor in the availability of the fuel. Supplying 500 gallons of product to a grass strip airport can be critical if you are the one who might be there at the time.

Therefore, when alternate fuels are considered, turbine fuel does supply an immediate answer since both the specifications and distribution system do exist. Perhaps turbine fuel is not absolutely perfect, but it is relatively better than the others. Nevertheless, new technology is needed here to answer the question: Which fuel? Some reasons have been stated, but these are based on available literature and limited inputs. The answer, whatever it is, needs to be "fire-proofed" from all aspects.

Once the question of which fuel has been answered, the question of which engine arises. The technological requirement can be substantial. Certainly new design spark-ignition, compression-ignition and stratified-charge engines have the potential to replace the current level SI engine. But the projections available show that moving to lower quality fuel for alternate engines means that some degradation in power or weight are inevitable. Granted, certain accessory devices have been proposed to recover this power loss, but these can fall more into the category of product development. Instead, it is the basic engine concept that needs investigation.

Understanding the combustion processes from practical engine data becomes a good vantage point. This may take the form of either single- or multi-cylinder engine testing to correlate the engine characteristics to combustion processes. For example, light-load operation of some diesel and stratified-charge engines has been reported as a critical condition; the flame can't get started, the engine quits, and the search for an answer is on. But wait. If you're agreeing with me, you are probably as guilty as I am in transferring basic automotive work directly to the GA application, essentially starting on the solution before the scope of the problem is defined. Our efforts should be directed to more primary investigations such as elimination of smoke, limited power

output, reduction or elimination of the requirement of an octane or cetane fuel rating, or the use of high temperature, perhaps ceramics, material for critical engine items. There is a fine line between what is a result of the design for automotive and what is needed for aircraft.

It appears as though I have neglected the turbine engine completely. Actually, this has been done because the turbine engine falls into a unique class within the present discussion. This engine has multi-fuel capability, but only some degree of multi-fuel compatibility. It is certainly a potential alternate to the current SI piston engine. Unfortunately, cost and efficiency continue to plague its downscaling to the piston engine horsepower range.

The gas turbine engine does demonstrate a multi-fuel capability, but from NASA projections, the turbine fuel will degrade in the future. The question arises as to how much will this alternate fuel degrade? A NASA-led working group has defined a broad specification fuel for the turbine as a potential answer.

Perhaps more important, will the future fuel characteristics affect the alternate engine choice of today? NASA work has been started to determine the effect of the broad specification fuel on turbine engine component life. Meanwhile, it is well known that some stratified-charge engines have a definite fuel octane requirement, while others operate more efficiently, or produce more power, on one fuel compared to others. Therefore, the choice of engine may well be dictated not only by the fuel availability, but also by the future characteristics of that fuel.

By now you should be asking which technology requirements are being defined. Actually only a few. But more importantly, what I am defining are more the prerequisites to technology. It is difficult and perhaps misleading to support a specific technology research area until the best available information has been stated and collectively agreed upon as to the most likely direction. We must define the problem before reaching for the solution. This need for problem definition is the last point I wish to cover, that is, the organizational aspects of new GA technology.

I propose a Research and Technology Advisory Committee (Figure 1), consisting of industry, government, university and independent representatives. This committee would be specifically charged with general aviation responsibility. Such a committee is not new. However, several years ago, such a group was absorbed into a large committee, and as such, lost its specific identity. Unfortunately, losing identity is comparable to losing direction and its ability to adequately address the current question.

To dramatize this point, take this workshop. We are in need of new developments in the GA industry, but just scheduling this workshop to assemble the right people at the right time has obviously been troublesome. I believe that a more compact group, representing a good cross-section of the concerned workers meeting at scheduled intervals can do more to further the technological needs of the GA industry.

In summary there are three possible paths for the GA engine with regard to technology:

1. Do nothing with the current engine, but insure that an avgas comparable to avgas 100 is available forever in unlimited supply.

2. Continue with the basic design concept used today, but improve the engine/aircraft package to more efficiently convert the fuel to horsepower and transportation. This effort would require that the tools of engine analysis and design be made available. Essentially this approach recognizes a decreasing availability of avgas but conserves as much as possible.

3. Develop a new engine defined for an alternate fuel that could be introduced into the GA marketplace.

No single approach can be pursued alone. All of these must be addressed. Current engines will be in use for many years and new alternates are also needed. Finally as a step toward achieving these goals within a reasonable time frame, an Industry/Research Committee is suggested. The time available to get with the flow is quickly passing. Our industry must start to become selfish with the research and new technology that is started. Good planning is the key. It is always assumed that any technology can be conquered if infinite time and dollars are at hand. Unfortunately, this group has neither. Perhaps it was best put by one of our old non-engineering types who said that it takes nine months from conception to the birth of a child; Mother Nature contols that, and there's not a thing you or I can do about it. From the start of product development to production of a general aviation piston engine, it takes five years. Mother Nature controls that too, and again, we can't do a thing about it.

It takes five years to go through product development (not <u>research</u> development, but <u>product</u> development) to certification. These five years should be the concern of everyone here.

THE STRUCTURE

OF THE ORGANIZATION

Figure 1.

FUTURE OF ALTERNATE FUELS FOR TURBINE ENGINES

Helmut Schelp
Garrett Turbine Engine Company

In studies conducted by Garrett for the NASA/GATE Program, the trend analysis of U.S. general aviation aircraft shipments for the past 25 years showed the following average annual compounded growth rates as: (Figure 1)

Single-engine piston - 4.3% per year
Twin-engine piston - 4.4% per year
Turboprop - 9.2% per year

The combined growth trend of 4.4% reflects the strong contribuiton of the single-engine segment, which accounts for more than 80% of the total shipments. By 1988, the total shipments of general aviation aircraft is shown to be approximately 25,000, of which between 850 and 900 are turboprop. In actual fact the shipments for 1980 exceeded the forecast of this study which was projected from 1977 data.

Also from the GATE study, the potential 1988 turbine-engine production that could replace piston engines on a rational cost basis is shown for a range of horsepower classes (Figure 2). The agricultural applications included in this chart are there because the market survey indicated these aircraft would use a turbine engine. The 300-375 hp class is shown to offer the highest potential production primarily because of the contribution of the light twins and heavy retractable categories. The total potential replacement of piston with the turbine engines by 1988 is shown to be on the order of 11,000 to 12,000 units, which would represent a significant increase over the aircraft projections shown in Figure 1.

Garrett, or the Garrett Turbine Engine Company as we are now to be known, has been concerned with the prospect of utilizing alternate fuels for several years, arising from the fuel crisis of 1973-74. One of the earlier, and more optimistic, proponents of the gas turbine made the statement that his engine had a wide-ranging appetite for fuel and could burn about everything but old army boots. It may not be too far in the future before we begin considering how we even grind these up and "boot" them into the combustor.

Although this presentation is oriented to alternate fuels for turboprop engines used by general aviation aircraft, the base of this technology is derived from a rather wide variety of gas turbine products at Garrett as shown in Figure 3.

The TPE331 turboprop began development in 1959 and was first certified for commercial use in 1965 with a rating of 575 hp. Through the years the rating of this basic frame-size engine has increased to 1000 hp. Over 7000 engines have been produced for use on 66 different aircraft models including commercial and military applications. The total flight time is close to 20 million hours. A larger growth engine is now under development for 1500 hp.

The IE831 industrial engine with continuous power rating of 690 hp utilizes the same basic rotating components as the TPE331 turboprop. The major design difference in

the gas-flow path is the single can-type combustor in the industrial engine as compared to the annular reverse flow combustor in the turboprop. Where the turboprop operates primarily on aviation turbine fuels, the industrial engine is capable of operation on a variety of gaseous fuels, normal distillates including diesel fuel, and heavier fuel oils. The IE831 engines have accumulated many thousands of hours of operation on diesel fuel in applications such as the Alaskan pipeline and offshore drilling platforms.

The TFE731 turbofan, also widely used on general aviation aircraft, has thrust ratings in the range of 3500 to 4000 pounds. Garrett's entry into the gas turbine market was with APU's which today are on most major commercial airfraft, with few exceptions. The GTCP36 model illustrated in this Figure (3) is used on several of the newer general aviation aircraft for main engine starting and electrical power generation on the ground.

The GT601 truck engine is the product of a consortium development program that includes Mack Truck, another member of the Signal Companies along with Garrett, and KHD in Germany. This engine utilizes a recuperative cycle to achieve low specific fuel consumption and operates primarily on diesel fuel.

Figure 4 shows typical properties of current fuels used in the various models of Garrett turbine engines. For application in civil aircraft, Jet A is the most widely used fuel. The wide-cut (wide range of distillation temperatures) JP-4 fuel is primarily used by the U.S. Air Force.

Aviation gasoline is approved for emergency use in Garrett aircraft turbine engines. TPE331 turboprop engines permit the use of 250 gallons of civil grade 100 LL (low lead) avgas during any 100 hours of operation. A maximum limit of 7000 gallons is prescribed during any overhaul period* to avoid excessive buildup of lead deposits. The engine control system provides a specific gravity adjustment to maintain appropriate fuel metering schedules that will accommodate variations in fuel density.

Diesel fuel is primarily intended for industrial ground power and vehicular applications, but has demonstrated operational capability in a TPE331 turboprop engine.

The fuel properties of significant note with respect to combustion performance are the aromatic and hydrogen contents. As aromatics increase and hydrogen content decreases, the combustion flame tends to be more luminous from carbon particles, produces increased smoke and emits higher radiation that raises combustor wall temperatures. The higher freeze point and viscosity of the heavier diesel fuel, of course, also impose restrictions on low temperature and altitude starting capabilities. The heating values on a BTU/lb basis are shown to decrease with decreasing hydrogen content, but the volumetric heat content (BTU/gal) increases slightly because of the higher density of the fuel.

Figure 5 shows the extent of lead deposit buildup that was observed after 169 hours of operation in a T76 turboprop engine which is the military version of the TPE331. The fuel was a military grade 115/145 aviation gasoline which is allowed to contain 4.6 ml

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*Current TPE331 overhaul periods are 3000 to 3600 hours.

of tetraethyllead (TEL) per gallon of fuel.* The amount of avgas consumed during this test was about 8000 gallons. The post test condition was considered to be excellent with only slight deterioration in performance.

Considerable interest has been expressed by operators of agricultural aircraft to utilize diesel fuel which is readily available in most farming communities. To assess this capability Garrett conducted a series of combustor rig tests, engine endurance tests and flight tests with a commercial regular grade two diesel fuel. Figure 6 illustrates the ground starting, airstart and flight operating range that was investigated. Starting and operation were found to be acceptable with the restricted flight conditions of above 15°F temperature and below 15,000 ft. altitude as compatible with agricultural aircraft use.**

With regard to alternate fuels for turbine engines, the near-term situation, perhaps by 1985, may dictate the use of broadened properties beyond the limits currently specified for aviation jet fuels. This prospect became a reality to a limited extent during the 1973-74 fuel crisis, and the period immediately following, when emergency measures were needed in the U.S. to permit deliveries of Jet A above the specification limit of 20% aromatics. The current specification for civil aviation Jet A fuel now allows deviations up to 25% aromatics by proper notification from the supplier to the user. More recently, through the coordinating efforts of NASA and representatives from various segments of the aircraft and petroleum industries, a broadened range of fuel properties was defined for consideration in design and testing of engines and aircraft systems where the future use of possible near-term alternate fuels are concerned. This fuel has beome known throughout the industry as ERBS which is an acronym for Experimental Referee Broad Specification. In contrast to Jet A, ERBS allows a higher end point distillation on the order of 650°F, a higher freeze point of -10°F maximum and a lower hydrogen content of 12.8% which corresponds to an aromatic content of about 30%. The intent of ERBS, however, is to serve as an industry referee fuel for design consideration and evaluation testing of future engines rather than necessarily to set a standard of specification.

Alternate fuels derived from shale oil and coal are other potential sources for alternate fuels because of their plentiful supply in the U.S. The most probable product that is envisioned to offer a significant source of supply in this decade is a JP-4 jet fuel which is used primarily by the U.S. Air Force. Since this fuel is intended to meet current military specifications for JP-4, the resultant aircraft performance and

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*The 115 indicates the knock rating at lean mixtures such as encountered at cruise conditions while the 145 is the knock rating at rich mixtures for full power or takeoff, particularly where the use of supercharging is involved.

The TEL contents of other grades of avgas for civil aircraft use are as follows:

GRADE	TEL, ml/gal max.
80	0.5 - this grade is now in scarce supply
100	3.0
100LL	2.0

**TPE331-2-201A is FAA approved for use of diesel fuel Grade 2-D. Operating procedures are prescribed with respect to fuel handling (filter and water separator treatment in fueling) and special flight inspection precautions.

durability are expected to be equivalent to current petroleum products assuming all bases are covered, and this is intended to mean "technical bases," not "tactical air bases."

Coal liquids that have been evaluated thus far in Garrett turbine engines have been in the middle distillate range with volatility characteristics quite comparable to diesel fuel. The major differences have been low hydrogen contents, on the order of 10% with attendant high aromatics and high fuel-bound nitrogen in the range of 0.5 to 1.0%. The H-coal was obtained from Hydrocarbon Research and tested in a small APU. The SRC-II (Solvent Refined Coal) was produced by Gulf and supplied by DOE for evaluation tests in the IE831 industrial engine. These tests are still in progress.

Other fuels offering replenishable sources of supply are the alcohols and alcohol-fuel blends. The major drawbacks of these fuels for aircraft use are the relatively low heating values. Methanol at 8644 BTU/lb has approximately 45% of the heating value of aviation gasoline, while ethanol (grain alcohol) at 11,604 BTU/lb has about 60%. Also, the alcohols do not offer the same advantage of being an octane improver for use in gas turbine engines as for piston engines. Still, one has to consider that the alcohols are better than Army boots.

Garrett's experience with alcohol thus far has been in the development and delivery of IE831 engines to Brazil for operation on an ethanol base fuel. This will be described in some more detail on a later viewgraph.

Perhaps of major concern with the use of alternate fuels is the effect that increased aromatics, as characterized by lower hydrogen content, have on combustor wall temperatures. The aromatic compounds tend to burn with a smoky flame that emits higher radiation to the combustor walls. Figure 7 illustrates this effect as evidenced in the Garrett TFE731 Turbofan engine operating at takeoff thrust. Peak wall temperatures were 25°F to 95°F higher with ERBS fuel than when operating on Jet A. This could have a significantly adverse effect on combustor life.* Increased or more effective wall cooling would be necessary in the primary and intermediate combustion zones, but this in turn could have an adverse effect on lean limit stability and combustion efficiency at low power. So the solution is not a simple one.

The increased smoke formation from the more highly aromatic fuels is shown correlated as a function of decreasing hydrogen content in Figure 8.** Curves are shown for the TPE331 turboprop that utilizes an annular reverse-flow combustor and the IE831 industrial engine that operates at nearly identical cycle conditions but uses a single can-type combustor. The annular combustor operates at nearly half the space heating rate as the can-type and offers a longer residence time for combustion and carbon particle burnout. Both engines, however, would comply with the EPA smoke standards for turboprop engines in this size class even with the lowest hydrogen content fuel shown here which is diesel fuel. The EPA maximum allowable limit for the TPE331-8 turboprop engine is a smoke number of 45. However, the EPA concern in regulating the smoke number

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*Combustor life might be reduced by as much as 50% if ERBS fuel were used directly in place of Jet A based on the observations of this TFE731 engine test.

**Hydrogen content takes into account the various types of aromatics that may be present such as the single-ring and multiple-ring compounds.

is to control the exhaust emissions below the threshold of visibility. Another concern, of course, is the higher particulate concentration that results with the lower hydrogen content fuels and the possible long-term effects that this will have on turbine blade erosion and fouling of heat exchanger surfaces in the case of recuperated engines such as the GT601.

The alternate fuels tests conducted thus far at Garrett have shown no significant effect of fuel type on combustion efficiency within the range of light to middle distillates. Figure 9 compares the combustion efficiencies measured from exhaust emissions of an APU operating at idle which is considered to be most severe from an efficiency standpoint. The diesel fuel and H-coal varied by less than a half percentage point from the aviation turbine fuels and ERBS. Low temperature and altitude starting limits of these fuels, however, would be governed by viscosity characteristics and freeze or pour points.

NO_x emissions are produced not only by thermal fixation in the combustion process of the nitrogen* in the air, but also will form from nitrogen compounds in the fuel. Aviation gasoline, the jet fuels and diesel as shown in Figure 4, do not contain any significant amount of nitrogen compounds. However, the synfuels, and the coal liquids in particular as experienced at Garrett, contain appreciable quantities of nitrogen compounds. Figure 10 illustrates the contribution to NO_x emissions from the fuel nitrogen content as determined from doctoring regular diesel fuel with pyridine (C_5H_5N), a nitrogen bearing compound, determined from an IE831 engine test. This test indicated that about 40% to 50% of the nitrogen in the fuel converts to NO_x in the exhaust for this engine which is rather typical. Although combustors with lean primary zones have demonstrated moderate reductions in NO_x emissions formed from thermal NO_x, a rich-to-lean concept appears to offer the most promise to control NO_x formation from the fuel-bound nitrogen, as well as from the thermal fixation mechanism. (The principle of the rich-to-lean concept is to govern the formation of nitric oxides by initially reacting the fuel in an oxygen-deficient atmosphere where NO concentrations are low and then quickly transitioning to fuel-lean conditions.)

High nitrogen content in fuels is undesirable not only from a NO_x emission standpoint; it also contributes to poor thermal stability of the fuel. A fuel must afford the necessary thermal stability to prevent decomposition in the fuel passages that could form deposits and cause plugging of the fuel injectors. For this reason, the restrictions on thermal stability may also provide some measure of control on fuel nitrogen content and thus alleviate the concerns for appreciable NO_x emissions from this source.

As previously mentioned, Garrett has developed and delivered IE831 industrial engines that operate on a Brazilian alcohol fuel. The primary constituents of this fuel are ethanol and water, and a representative net heating value was determined to be 9763 BTU/lb. Due to import difficulties the fuel was simulated at Garrett by blending

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*Zeldovich Reactions:

$$N_2 + O = NO + N$$
$$N + O_2 = NO + O$$

denatured ethyl alcohol* with about 10% water. Engine performance with respect to fuel consumption was about 80% higher than with diesel fuel which corresponds on the order of the relative fuel heating values. NO_x emissions, on the other hand, were 40% lower due to the lower flame temperatures which were brought about in some measure by the water content in the fuel. The only major problem encountered in converting the engine to alcohol use was with respect to designing the fuel pump for durable operation with the reduced lubricity of the alcohol fuel.

In summary, the fuel property variations that have been identified thus far to be of concern with the utilization of alternate fuels for aircraft turbine engines are related in Figure 11 to the potential problem areas. Perhaps the effect of increased aromatic content presents the greatest initial challenge for development of innovative combustion design technology. However, all of these problems will need to be addressed in varying degrees.

The solutions of these problem areas will require various means of research and technology developments as indicated by the following:

Fuel property characterization is needed, for example, for accurate determination of hydrogen content and compositional analysis of types of hydrocarbon compounds, particularly the various aromatic structures, that may be present in alternate fuels. Also, lubricating properties need to be quantified and lubricity improvers such as the corrosion inhibitor HITEC E515 (formerly Santolene C) might be investigated for potential merit as an additive to alcohol.

Fundamental combustion studies are needed to determine critical design parameters for alternate fuels such as the auto-ignition temperature, ignition delay and droplet burning rates.

Advanced fuel injection concepts are needed to accommodate the small flow capacities required for the lower power range of the turboprop spectrum as identified for the future General Aviation turbine engine market. Possibilities such as pulsed sprays employed in diesel engines need to be explored as a means to obtain a high turn-down ratio in the ultra low flow range.

Alternate fuel design technology is needed, particularly for small annular combustors with small channel heights which are most sensitive to wall quenching effects and have high surface-to-volume ratios that compound the wall cooling problem.

Engine performance, endurance and flight test programs are needed to relate the alternate fuel effects to durability and operational limitations. Design tradeoffs will also require extensive evaluation by these means.

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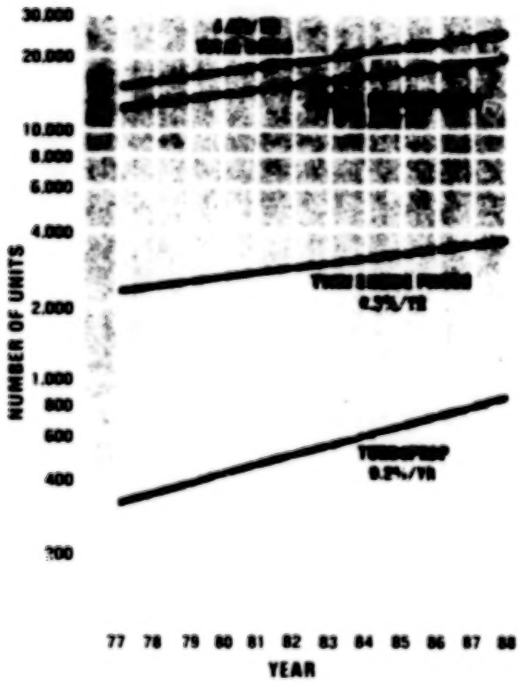
*Denatured alcohol:

100 gallons ethyl alcohol (C_2H_5OH), 190 proof
4 gallons methyl isobutyl keytone ($C_6H_{12}O$)
1 gallon gasoline

Finally, and perhaps even simultaneously, aircraft fuel system studies need to be conducted to assess the impact of alternate fuel properties on factors such as: compatibility with elastomers, effect of possible fuel additives under field service conditions, and operational safety.

FORECAST OF GENERAL AVIATION AIRCRAFT SHIPMENTS

(U.S. MANUFACTURERS)



GARRETT GATE STUDY
NASA CONTR. NAS3-20755

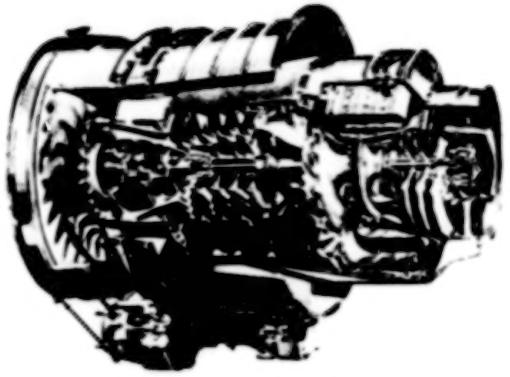
Figure 1.

POTENTIAL GENERAL AVIATION TURBINE ENGINE DEMAND FOR 1988

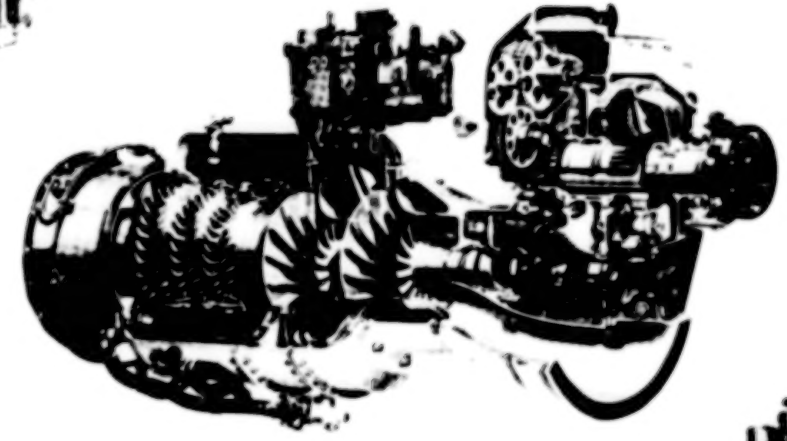
AIRPLANE CATEGORY	HORSEPOWER CLASS			
	225–275	300–375	450–550	550–650
AGRICULTURAL	636	665	398	134
PRESSURIZED TWIN			1,414	828
CABIN CLASS TWIN			294	644
LIGHT TWIN	1,108	1,788		
HEAVY RETRACTABLE	270	1,816		
LIGHT RETRACTABLE		159		
FIXED GEAR HI-PERF		731		
UTILITY		555		
TOTAL	2,014	5,714	2,106	1,306

Figure 2.

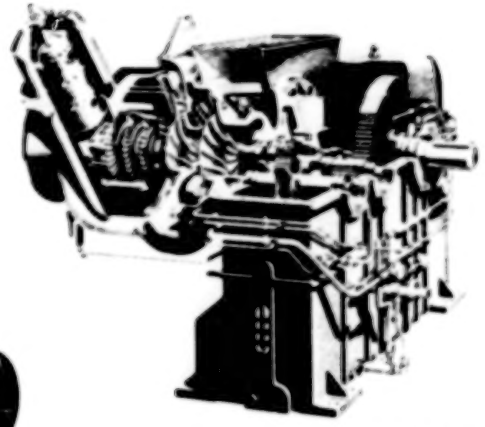
ALTERNATE FUELS PROGRAMS



TFE731 TURBOFAN

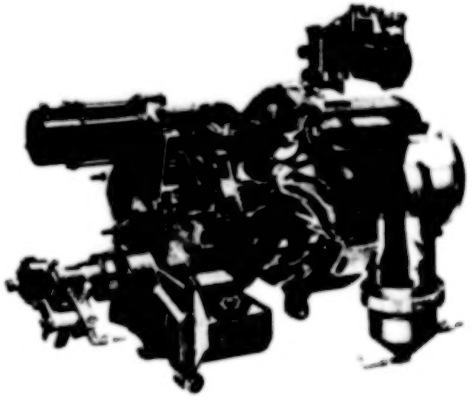


TPE331 TURBOPROP



IE831 INDUSTRIAL

GTCP36 APU



GT601 TRUCK

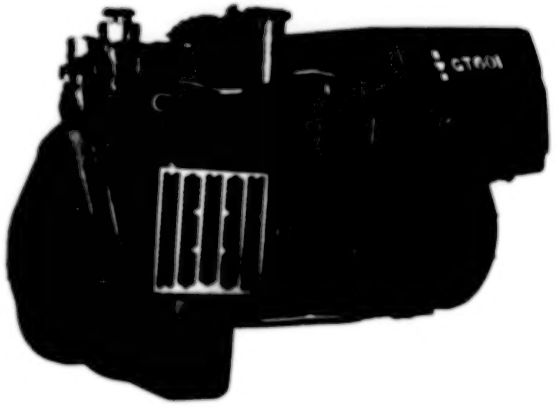


Figure 3.

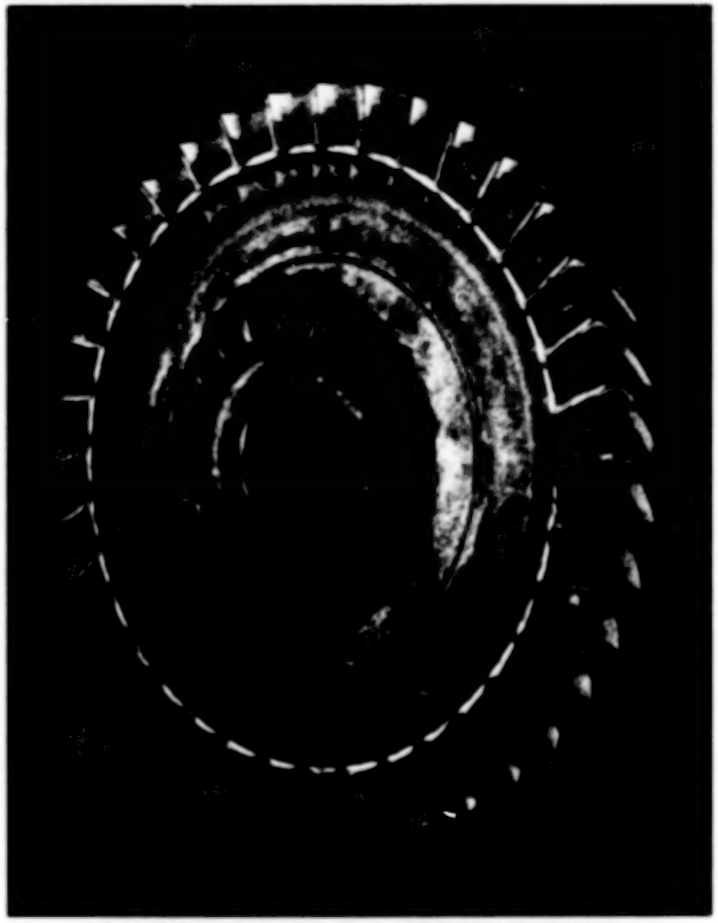
TYPICAL PROPERTIES OF CURRENT FUELS USED IN GARRETT TURBINE ENGINES

PROPERTY	AVGAS 100/130	JP-4	JET A	DIESEL DF-2
SPECIFIC, GRAVITY AT 60°F	0.706	0.790	0.819	0.851
DISTILLATION TEMPERATURE, °F				
INITIAL BOILING POINT	117	136	315	365
10% EVAPORATED	175	240	365	430
50% EVAPORATED	209	335	418	516
90% EVAPORATED	230	445	474	609
END POINT	283	502	512	658
VISCOSITY, cST @ 100°F	0.53	0.99	1.57	3.15
AROMATICS, VOL. %	2.5	14.9	17.3	25.1
HYDROGEN CONTENT, WT. %	15.6	14.2	13.9	13.0
NITROGEN CONTENT, WT. %	NIL	NIL	NIL	0.037
SULFUR CONTENT, WT. %	0.02	0.06	0.11	0.29
NET HEATING VALUE, BTU/LB	18,750	18,600	18,530	18,300
FREEZE (POUR) POINT, °F	< -76	< -72	< -52	(5)

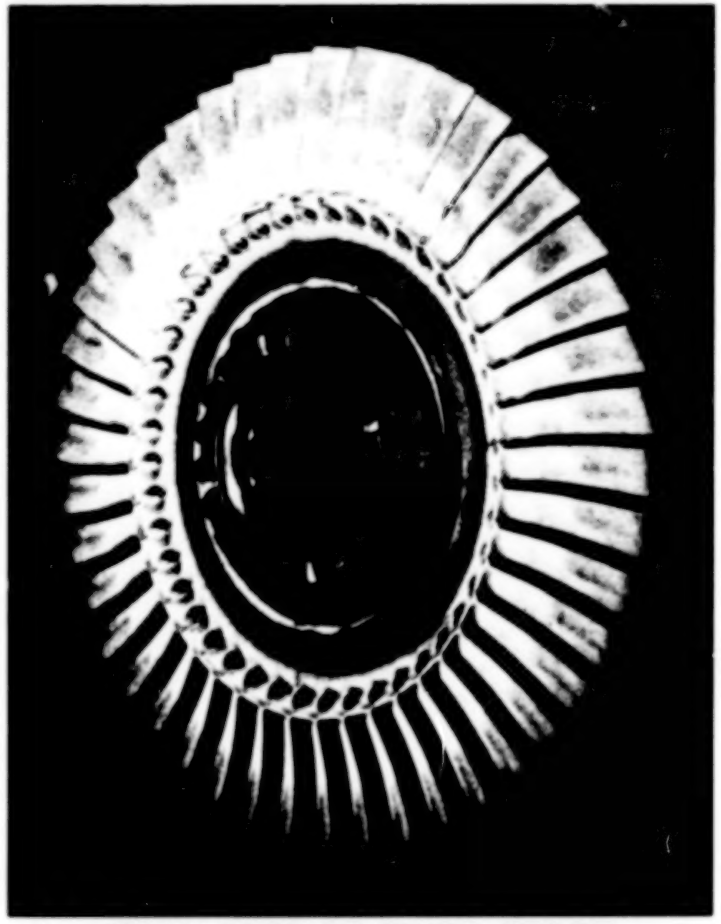
Figure 4.

T76/TPE331 TURBOPROP ENGINE USE OF AVGAS

169 HOURS OF ENGINE OPERATION AND 167 STARTS WITH AVGAS GRADE 115/145



FRONT FACE OF FIRST STAGE
TURBINE WHEEL



REAR FACE OF THIRD STAGE
TURBINE WHEEL

Figure 5.

117

TPE 331 TURBOPROP FLIGHT TEST WITH DIESEL FUEL

SHORT BROTHERS SKYVAN

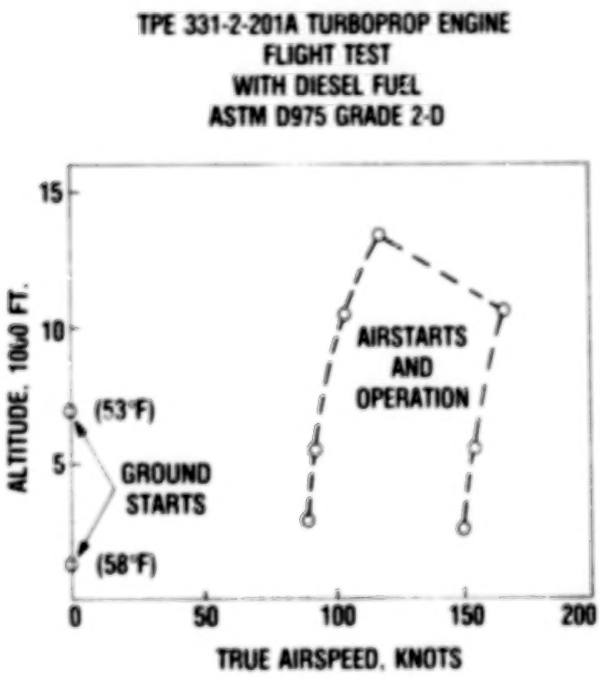
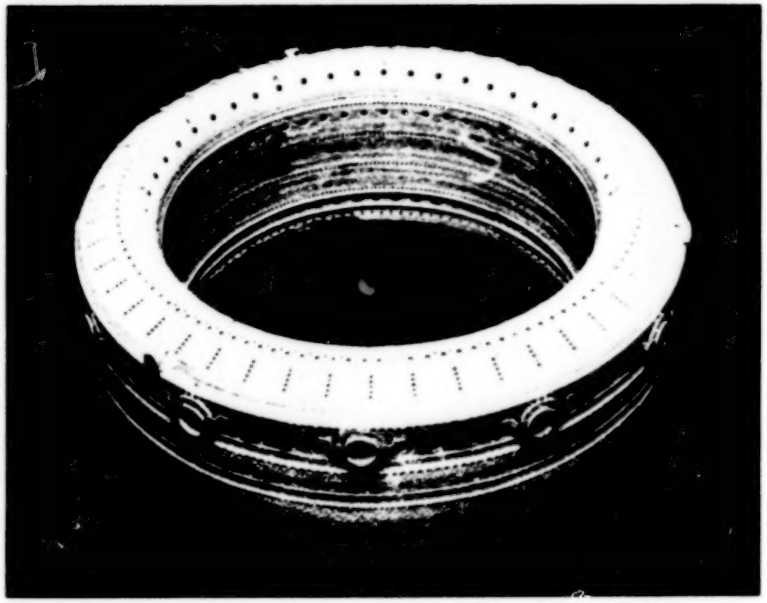
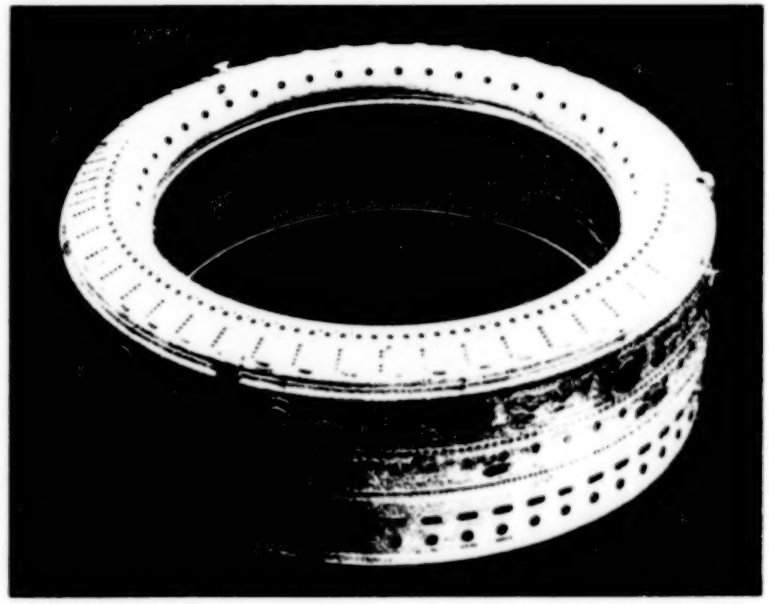


Figure 6.

COMBUSTOR WALL TEMPERATURE COMPARISONS BETWEEN JET A AND ERBS FUELS

- TFE731 TURBOFAN ENGINE AT RATED TAKEOFF THRUST





JET A		ERBS
17.3	AROMATIC CONTENT, VOL. %	29.6
13.9	HYDROGEN CONTENT, WT. %	12.8

- PEAK WALL THERMOCOUPLES INDICATED 25 TO 95°F HIGHER WITH ERBS FUEL

Figure 7.

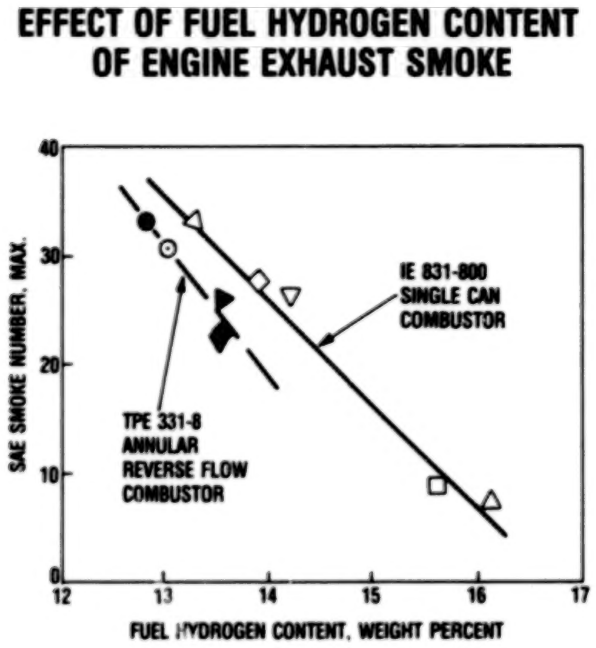


Figure 8.

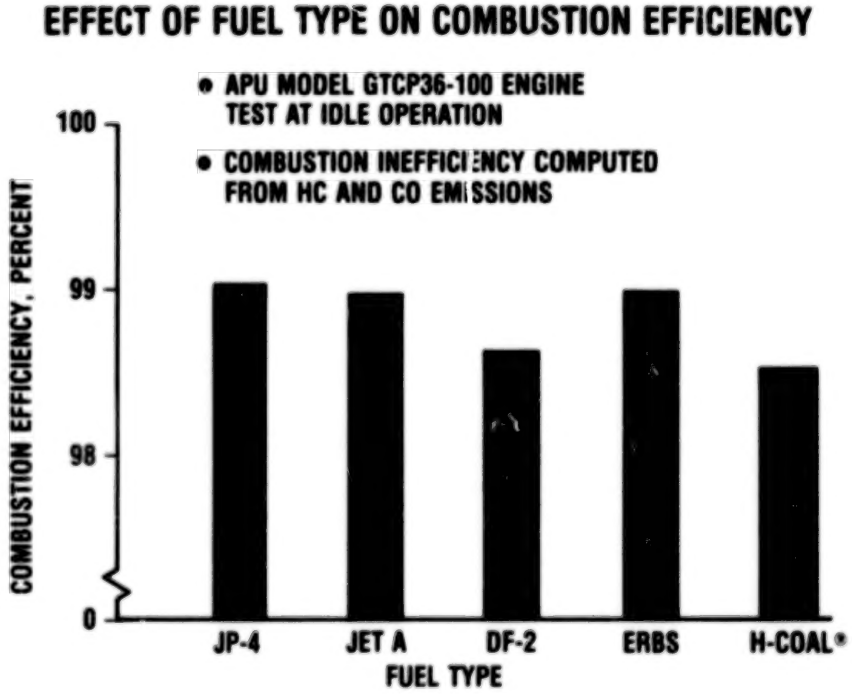


Figure 9.

EFFECT OF FUEL NITROGEN CONTENT ON NO_x EMISSIONS

IE831-800 INDUSTRIAL GAS TURBINE ENGINE AT MAXIMUM CONTINUOUS POWER

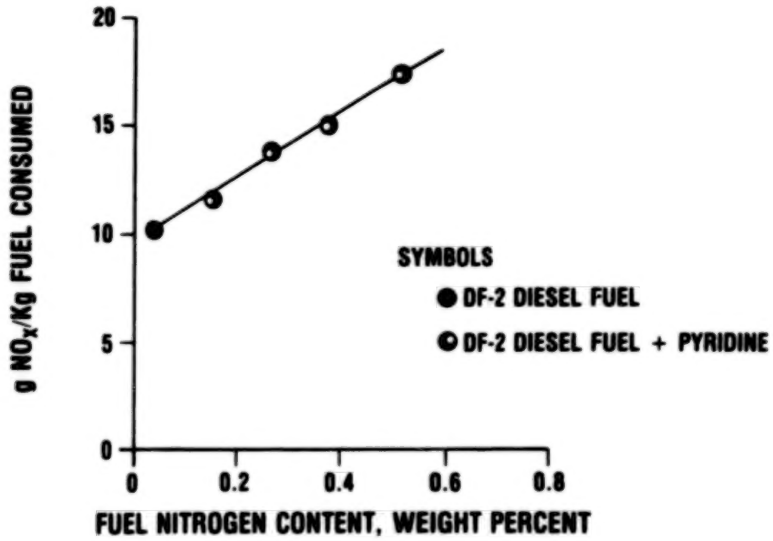


Figure 10.

POTENTIAL PROBLEMS WITH ALTERNATE FUELS FOR AIRCRAFT TURBINE ENGINES

FUEL PROPERTY VARIATION	POTENTIAL PROBLEM AREA
INCREASED AROMATICS (LOWER HYDROGEN CONTENT)	HIGHER COMBUSTOR WALL TEMPERATURES WITH REDUCED DURABILITY
	INCREASE EXHAUST SMOKE AND PARTICULATES
INCREASED VISCOSITY	RESTRICTED LIMITS FOR STARTING
INCREASED FREEZE OR POUR POINT	REQUIREMENT FOR FUEL HEATING OR RESTRICTED FLIGHT CONDITIONS
INCREASED NITROGEN CONTENT	INCREASED NO_x EMISSIONS
REDUCED HEATING VALUE (BTU/LB)	INCREASED SFC AND REDUCED FLIGHT OPERATING RANGE FOR FIXED GROSS WEIGHT
REDUCED THERMAL STABILITY	FUEL SYSTEM (NOZZLE) PLUGGING
REDUCED LUBRICITY	EXCESSIVE FUEL PUMP WEAR

Figure 11.

ADVANCED ROTARY ENGINES*

Charles Jones
Curtiss-Wright

To provide background, Figure 1 shows the gasoline workhorse engine that Curtiss-Wright has built over the years, although it has not been an active product since the mid 1960's. The basic power section of this rotary engine was designed in 1958. It ran for the first time in 1959, and was finally developed into what we felt was a durable powerplant in mid 1962. It was tested at all of the big three automotive companies, and it served as the workhorse for most of our field installations, in particular our exposure to aircraft.

However, it is not an aircraft engine. It's rated very moderately with emphasis at the low speed end for automotive use and about the only thing it demonstrated in flight was its particular qualities of quiet operation, smoothness and balance, and reliability as well, although the tests were not endurance tests. This engine was the basis of all our future work and this general size relates to projected engines.

The engine has two rotors and sixty cubic inches per shaft rotation. This engine flew for the first time in a Schweitzer glider on a U.S. Navy "Q-Star," "Quiet" airplane program. It has a large low speed propeller and the vehicle itself was modified. It was extremely quiet. The prior engine was a 100 horsepower continental and was also very quiet.

The advantage is that both installations enjoyed a large muffler system, but in this case, with the absence of valves, it was possible to fly 200 feet overhead and not be heard. The RC2-60 also flew in a Cessna Cardinal 177 (two versions), and in a Hughes TH55 helicopter.

The Marvel-Schebler carburetor and a Bendix magneto were current at the time. This RC-75 engine (Figure 2) was designed in the late '60's, and developed in the early '70's. With this engine, we were faced with the same problem that has been mentioned here by several others. About 1973 we were talking to many of the FAA people that are here today about certifying this engine. But at the same time, we were also concerned about critical fuel availability in a broader sense, and our prime interest at that point, as a licensor of Wankel engine technology, was automotive. However, the important theme was better efficiency and broader fuel capabilities, and while in my opinion this is not true to the same extent with some of the other concepts, the basic technology holds over a very wide application range for the rotary engines, as I will try to briefly illustrate.

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*This presentation is based on a paper Multifuel Rotary Aircraft Engine by C. Jones & M. Berkowitz, Curtiss-Wright Corp., presented before the 16th Joint Propulsion Conference, sponsored by the American Institute of Aeronautics and Astronautics, Society of Automotive Engineers and the American Society of Mechanical Engineers, June 3 - July 2, 1980, Hartford, Connecticut.

Our point was that we felt that stratified charge, which was particularly suited to the rotary, Wankel-type engine, covered some of its homogeneous charge deficiencies as well as exploited some of its geometry advantages, had potential which had not yet been realized. We felt that that could produce better fuel economy and that it would be of interest to the country. So before proceeding with this engine we redirected our efforts back to the basic research on stratified charge. During the period from 1973 to 1976 we concentrated on this area.

To start with, there are basic reasons why a rotary engine has an inherent advantage in terms of compact size and high power density. First of all, it is not limited by valves. Even though it's performing the same four stroke function, it's doing this without valves, thanks to the geometry (Figure 3). This removes the limitations of speed as imposed by the dynamics of a valve system and also by breathing limitations. It further enhances this capability for higher speed because it's completely balanced. The timing device, which is a gear, causes the rotor to turn at one-third of the shaft speed, but its center of gravity remains at a fixed distance from the axis of the shaft. That means that it can be completely balanced either in a single rotor unit, or two rotors, or any combination. This of course leads to use of multi-rotor engine families, but it also provides the capability of running at high speed without any large unbalanced forces.

As shown in Figure 3, the amount of total working area on each of the three sides of the rotor, which are all performing functions at the same time, relative to the total frontal area, is very high. This means there is a lot of working volume per unit volume of the machine. As far as a gasoline engine is concerned, this geometry has friction and mechanical advantages but does not imply any specific advantage in terms of combustion performance efficiency. In fact, it has a minor disadvantage. The disadvantage is that there is not the ideal combustion chamber surface shape, which would be hemispherical, and because of the flame front traveling faster with the rotation direction, it is difficult to burn at the rear end of the chamber.

However, this does not show up in the fuel consumption efficiency of a well-designed rotary engine, which can match the BSFC of a reciprocating piston engine, but it does result in higher specific hydrocarbon emissions. When we consider a multi-fuel engine, that geometric difference is an advantage because what is common to all the stratified charge engines is the need for high velocity turbulence. This comes as a gift in the rotary (unthrottled) because the air charge is moved past the location of the spark plug and the nozzle and it does this without suffering the disadvantage of either a lower power output or friction loss of the reciprocating engine which has to induce this motion. The secret of the stratified charge is to inject the fuel and burn it at the rate it is injected. If you do this successfully, and you cannot do it without the turbulence, then you achieve the independence from either cetane or octane limitations. If this is one of the objectives, namely to gain independence from stringent octane or cetane specifications, then we have attained this result. I'm not referring to a concept, I'm talking about something that we're demonstrating in hardware.

Figure 4 shows the difference. The Honda is really a lean burn engine; it's not a stratified charge engine in the true sense. Ford Proco, which has been dropped, failed because it mixed the fuel and air before igniting the spark, so it was not multi-fuel. The Texaco is a multi-fuel stratified charge engine with essentially the same combustion process except that we believe the rotary is better adapted to that process. Incidently, Texaco Beacon Labs speaks with slightly different voices. Kurt Strauss mentioned his particular view earlier, but if Bill Tierny were here, he'd point out that

the studies at Texaco have shown that if the refineries were optimized for a middle distillate fuel, it would be possible to get more energy (BTU per pound) per barrel of crude. I'm not sure what the exact percentages are but apparently it is a significant number.

Our first stratified engine is shown in Figure 5. Larry Duke rightly mentioned that the problem with stratified charge is to get an engine that will run full range. It's not as critical a problem for an aircraft engine as it is for an automotive engine. I have to point out that a lot of our basic research was done with automotive applications in mind. Performance of this engine is not particularly spectacular, but to answer the starting question posed to a previous speaker, this engine started at -35°F with no aids, and it was multi-fuel. You can also see that roughly a 200 horsepower engine will fit into a two-foot cube. This particular combustion configuration which I will not describe, ran very well at the low end and not the high end.

Figure 6 shows an engine of about the same era that is air-cooled. To comment on the references concerning air cooling vs. liquid cooling; having made both engines, not only the rotary, but our reciprocating radial engines, we think there are compelling reasons that favor the liquid cooled at advanced outputs. At the particular outputs we are talking about today, it really does not make too much difference, but we think there are still advantages and we can debate that in the working session. However, this particular engine which was stratified charge, which is roughly a 300-pound engine for 300 horsepower, did not achieve the good low end performance, but did do well at the high end.

This was all before the major 1973-1976 effort that I briefly discussed. During that period we did find the combinations that would run full range and do this with any fuel and with fuel consumption that would match an automotive diesel. Basically this is the concept (Figure 7). The breakthrough really was not using a single injector but using a pilot injector whose prime purpose is to light the fire. A very small amount of fuel is injected from a single hole diesel-type nozzle, approximately 5% of the maximum fuel at any given speed and, adjacent to that nozzle is a spark plug that lights off consistently regardless of the power. The power is regulated by the main injector. We've run many variations of this and, in fact, one of the most promising at the end of that '76 period was one where the relative positions of the pilot and main were integrated. I'll show you some data on that later, since it subsequently turned out to be better.

Figure 8 shows brake specific fuel consumption vs BMEP. The various other published data curves that I'll leave out at this point show that we get essentially the same performance for hydrocarbons, NO_x or fuel consumption, for the same configurations, regardless of the fuel. I'm not saying they are identical, but I am saying they are very close, within a few percent. The bottom curves are data from that stratified charge engine compared to a Ricardo Mark V diesel which is the basic prechamber configuration most of the automobile people use. Also shown on Figure 8 are the Volkswagen naturally aspirated and turbocharged data which are generally consistent. They are derived from the Ricardo Diesel form as well. The essence of the curve, which is confusing because of the number of curves plotted, is that performance we have shown as of that date was better than the diesel for all except the maximum output.

We have since improved the high end of a larger engine under a military contract. If the engine is really smaller, lighter and has better fuel consumption, and will burn any fuel, then it has to be of interest. A comparison with the equivalent output

Volkswagen six cylinder diesel engine shows that indeed it is smaller and lighter. Now we did run briefly on alcohol, recognizing that the heating content is lower as has been mentioned here several times. We did not change our nozzles to pump more fuel through with the same timing. So it really wasn't a good test in the sense we didn't optimize for alcohol. However, for the particular run, and expressing the data as BTU per brake horsepower/hour, the data is practically on the same line for both 92 octane unleaded gasoline and methanol. Incidently, apropos the Garrett experience, there was no harm to the engine, but the next day our test stand fuel pump was out . . . unfortunately it was aluminum.

Now a little bit about where we go from here. As I said, the basic technology is there. Someone may ask, then why do you need NASA? Because of the special needs for aircraft which demand that the basic technology be extended to much higher outputs; to make the power density even higher, and at the same time further improve fuel consumption. Turbocharging is desirable also for altitude and higher power, etc.

However, there is another reason for turbocharging this engine. Unlike the gasoline homogeneous charge engine, it's not constrained to operate within narrow air-fuel ratio limits. It operates like a diesel throughout the same range, from 100 to 1, to 20 to 1 air-fuel ratio roughly. A diesel is somewhat flatter, but it does show the same characteristics, specifically if you would plot thermal efficiency vs air-fuel ratio, you will find that there is a range where the thermal efficiency is best. So one of the principle reasons we're interested in turbocharging is that we want to pump excess air in so that we have optimum combustion efficiency at the same or higher output. This was theory until a few months ago, but I'll show you some very recent data that will show it's not really a theory any longer. Higher or better thermal efficiency translates into better fuel economy.

Figure 9 shows the characteristic specific fuel consumption curve of the stratified charge engine. If we plot indicated specific fuel consumption (that is the inverse of thermal efficiency) vs F/A ratio, the bottom of each one of those curves is where the thermal efficiency is best. At any speed, fuel-air ratios in the range of 0.02 to 0.03 provide the best thermal efficiency.

The benefit of turbocharging is suggested in Figure 10. It permits the characteristic BSFC vs BMEP curve to be lowered at high output and avoid the loop where it comes up. We do that for two reasons. One because we're improving the thermal efficiency with excess air. We're not talking about waste gates, we're talking about pumping all the air through the engine. In addition we improve the fuel consumption because we're getting better mechanical efficiency by getting more output for essentially the same friction. So this last year, 1980, we had a company sponsored feasibility demonstration to see whether this theory would indeed work. We are clearly interested in aircraft engines, but in fairness, this is a common theme that applies to all the engines of interest for both automotive and military prototypes as well.

Briefly to show you some of the data, Figure 11 is from the same sixty cubic inch "BTC pilot" power section that I showed earlier. The top curve shows that because we're pumping through more air when we turbocharge, our fuel-air ratio is obviously changing. And we're limiting the mixture to not more than 0.025 fuel-air ratio. The brake specific fuel consumption curve, when naturally aspirated, has a characteristic upward loop at the high load end, which was eliminated when turbocharged. The improvement to the economy at a high power cruise point is about 19%, which is consistent with our predictions. Further, if you look for the turbocharged points, you can see that they

are all where the indicated specific fuel consumption, and thus the thermal efficiency is best.

We also ran with a lower compression ratio (6:1), and Figure 12 shows that the naturally aspirated brake specific fuel consumption was pretty poor. But when we turbocharged, it came very close to the standard 8-1/2:1, and it allowed us to run, with a given pressure limit on the engine, to much higher outputs. What this essentially showed is that the theory upon which we based the extrapolation of our current technology to the NASA proposal limits is confirmed. I should explain that we are not as far advanced in this design study as some of the other projects that have been described to you today. However, we are in the final stages of our study and as Dave Ellis mentioned, he is doing some of the systems tradeoffs for us. We are finding some surprises. The best fuel consumption engine is not the best for the aircraft as an overall system. We're reflecting this input as we finalize our work.

The real question is whether or not our technology scales down. All of the engines that we're talking about with NASA are smaller than the 60-inch size, in the range of 47 to 32 cubic inches. Now we know quite a bit about scaling the rotary engine. We've gone over a range of 500:1, but all on a gasoline engine. Prior to two years ago, we had never run a stratified charge engine with a different basic size than the 60 cubic inch or the 90 cubic inch discussed previously. The first one actually run, which was our first exercise in scaling stratified charge, was on the military program that we are running now for the Marine Corps mentioned by Bob Mount very briefly earlier.

Figure 13 shows that engine. Of course we are not proposing this as a general aviation engine; the engine is 1500 horsepower, and as you can see, is about the size of an office desk. It happens to be smaller and lighter than the regenerated gas turbine in the XM1 tank, an application of interest.

What we are doing now is actually developing half of that engine; split right down the middle. The engine is really two two-rotor engines coupled at the center, each of which is a 750 cubic inch, 750 horsepower engine. While Bob mentioned that this engine would be ready for production in the latter part of this decade, that schedule is really dictated by the military's need for the vehicle. If we had to produce this earlier, we could. In 16 months, engines are going out for a field test. We expect to run that field test in track vehicles and amphibious vehicles, and get quite a bit of data. But the real question was: did it scale?

ISFC vs IMEP is shown on Figure 14. Considering where in the power range these engines received development emphasis and that the same configuration was common to both even using the same nozzles and the same spark plugs, our conclusion is that it does indeed scale. It doesn't tell us whether it will scale in the opposite direction . . . smaller.

Now comparing the same data on a brake basis (Figure 15), you will see there is an advantage in the larger engine because of the lower friction. Looking at the two curves, both called BTC pilot, the larger engine actually has better brake specific fuel consumption. But I mentioned earlier that the reverse configuration has shown more promise, and indeed it did when we were able to develop it further. The lower curve is that reverse configuration which is now standard in the military engine. This is a fuel map for the two-rotor engine, and it's naturally aspirated. My point is that we can bring the BSFC down, into the mid three's or high three's at the same speed with higher power--0.34 - 0.32--depending on the BMEP, without going to a bottoming cycle or turbocompounding. Of course that could be added also.

The real question is what are we doing for NASA, and how do we see this in an aircraft engine? Figure 16 shows key features at both advanced and highly advanced designs. The idea is really to turbocharge, not just for altitude or more power, but to turbocharge with additional excess air so that we can realize the best possible fuel consumption. The "highly advanced" engine just does more of it. I think I mentioned that the 300 horsepower basic engine, the RC2-75, was 280 pounds dry and 358 pounds wet, ready to fly, and that included the heat exchangers which are relatively small. They are about 18 inches square and two inches high and they do fit within the engine compartment. They are considerably more efficient than a baffled cylinder head.

What we're talking about for this particular engine is 0.36 and 0.38 BSFC cruise. We can bring them down to about 0.34, but at a slight increase in weight and size. This is really the reason why we have very much appreciated the assistance of Dave Ellis at Cessna because analyzing it as a system he has shown that it wasn't necessarily the best fuel consumption engine that gave the best system efficiency. That's what we really wanted to know.

Figure 17 shows one of the highly advanced technology engines which is a two-rotor 32 cubic inch engine. It would fit in a 17-inch diameter tube and is relatively long. By now we have carried these studies a little bit further, and the engine would be even smaller than that. This figure does not include the heat exchangers.

In conclusion, Figure 18 summarizes the features of a stratified charge rotary aircraft engine.

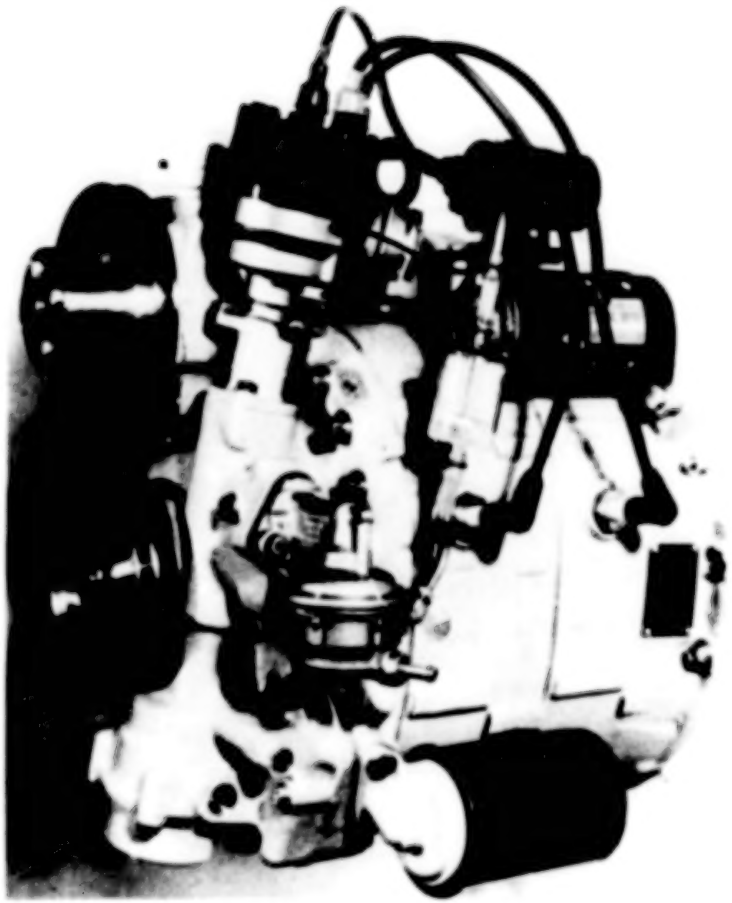


Figure 1. - RC2-60U5 automotive engine prototype

Figure 2. - RC2-75 aircraft engine prototype

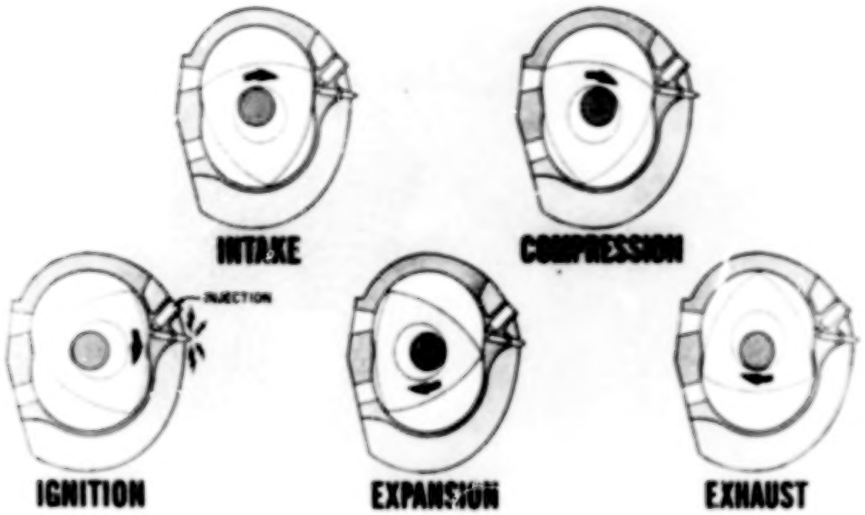


Figure 3. - Stratified charge combustion cycle

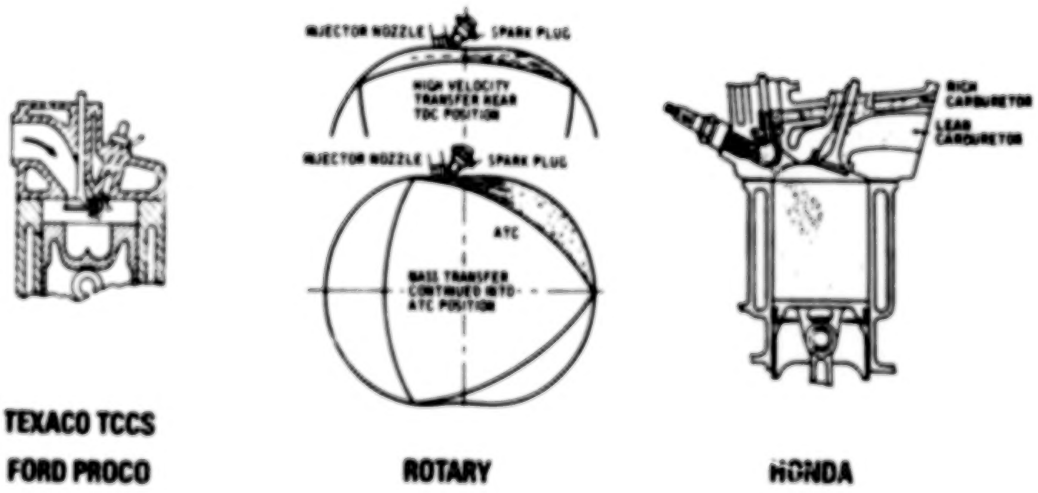
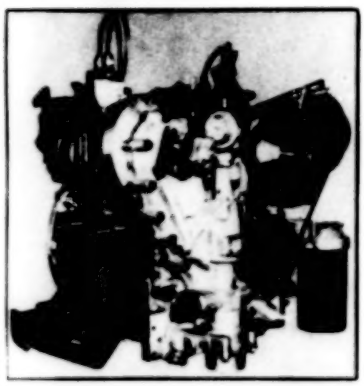


Figure 4. - Stratified charge processes

RC2-60U10 Liquid-Cooled Stratified Charge Engine (1965)

WEIGHT	294 LB
WIDTH	24 IN.
LENGTH	24 IN.
HEIGHT	24 IN.



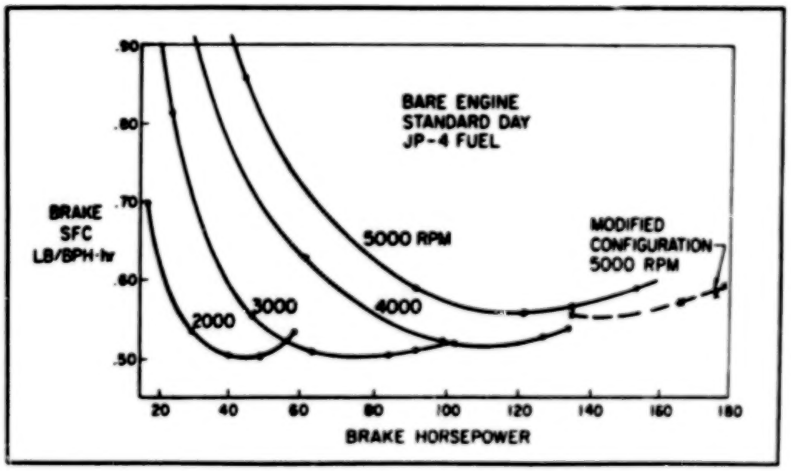


Figure 5.

RC2-90 Air-Cooled Stratified Charge Engine (1966)

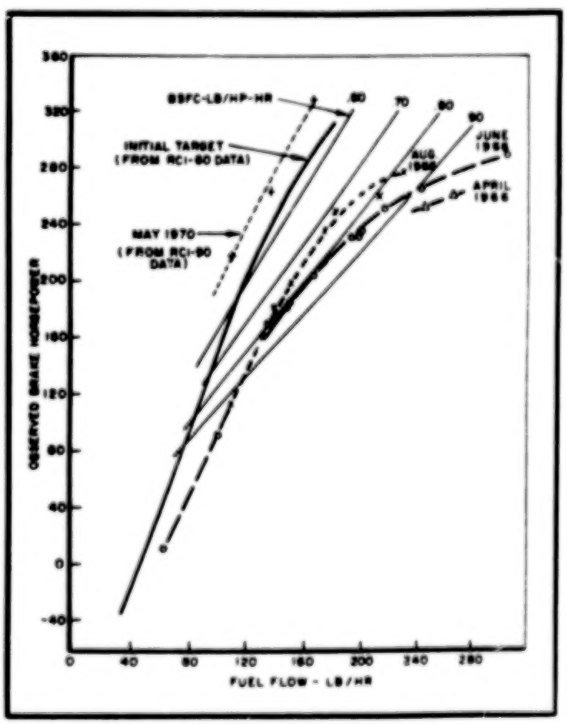


Figure 6.

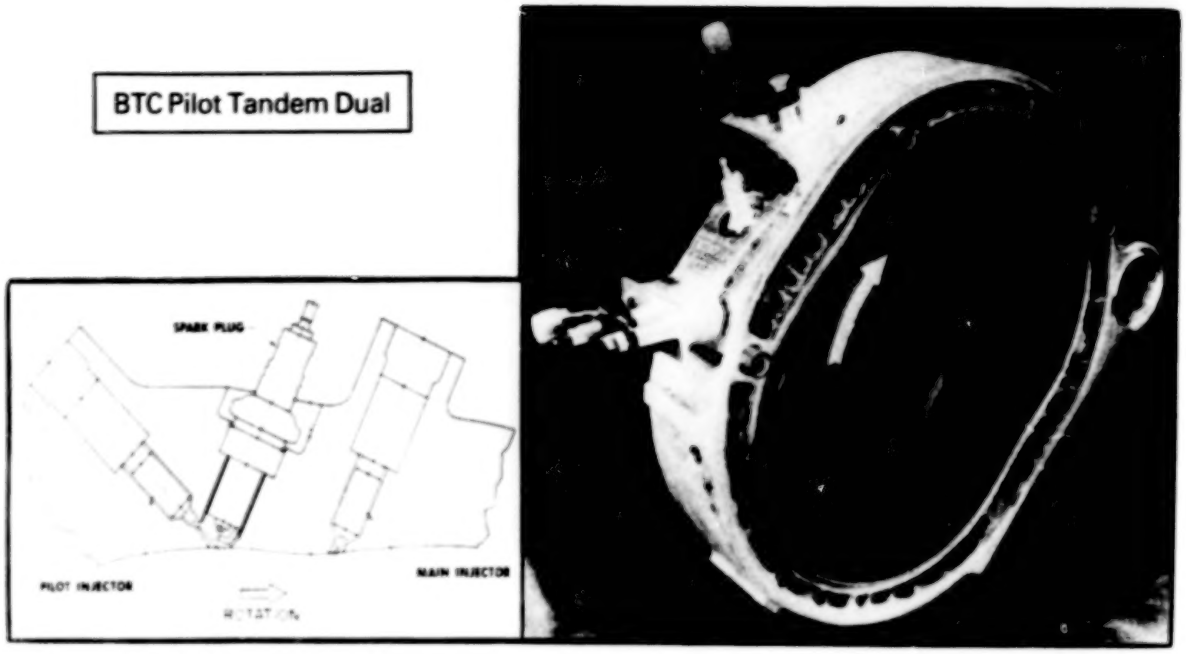


Figure 7. - Stratified charge RC1-60

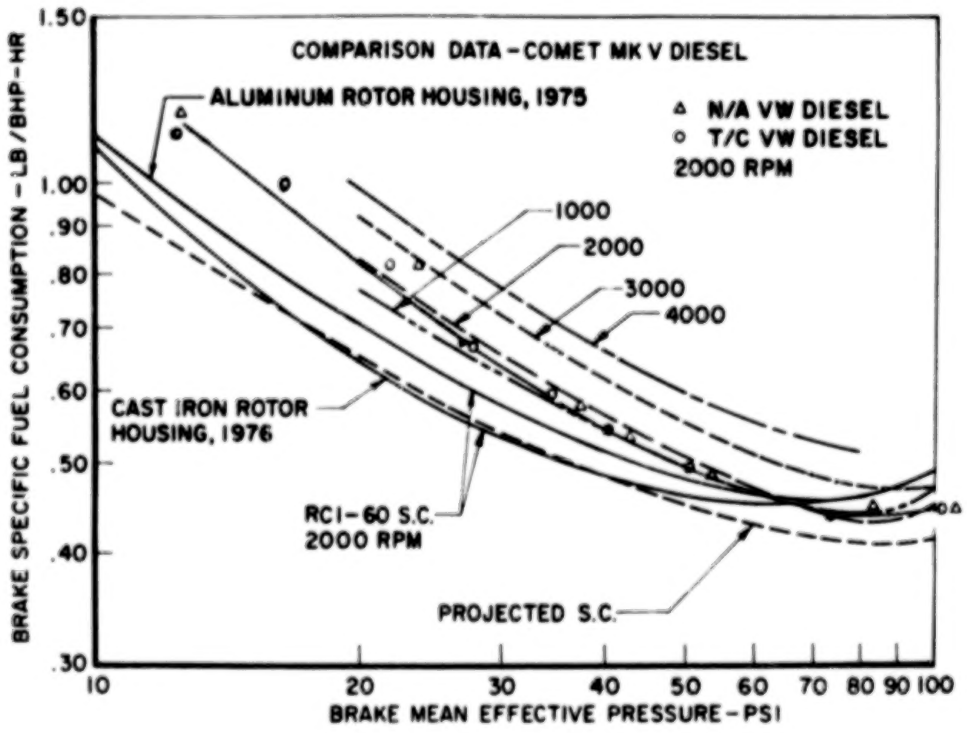


Figure 8. - Comparison data - BSFC vs BMEP

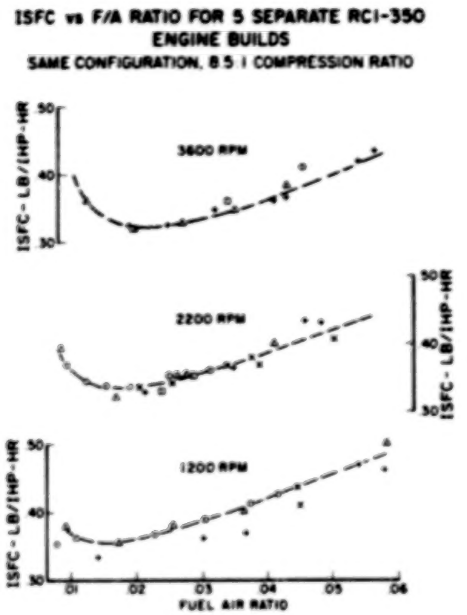


Figure 9.

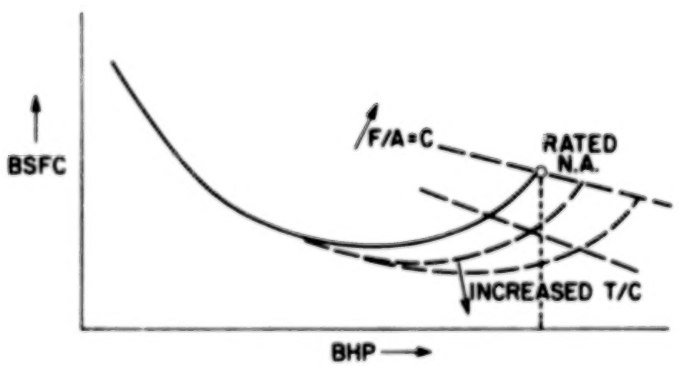


Figure 10. - Effects of turbocharging on power and economy.

RC1-60
STRATIFIED CHARGE
4000 RPM
PERIPHERAL
INTAKE PORTS

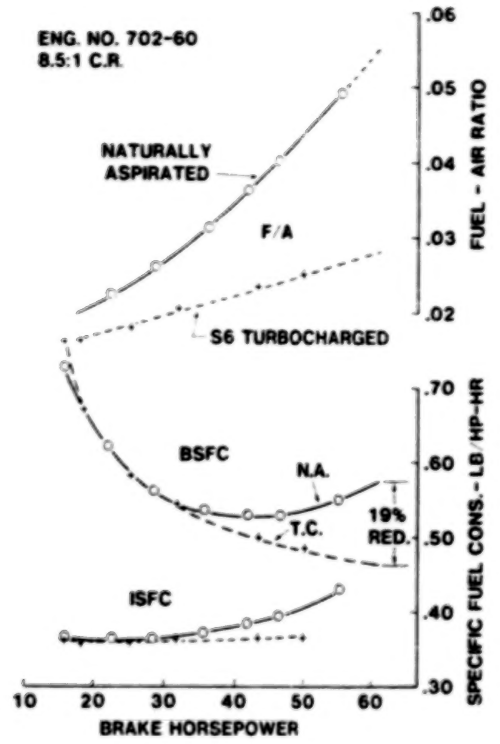


Figure 11.

STRATIFIED CHARGE
ROTARY COMBUSTION
ENGINE PERFORMANCE
8.5:1 COMP. RATIO

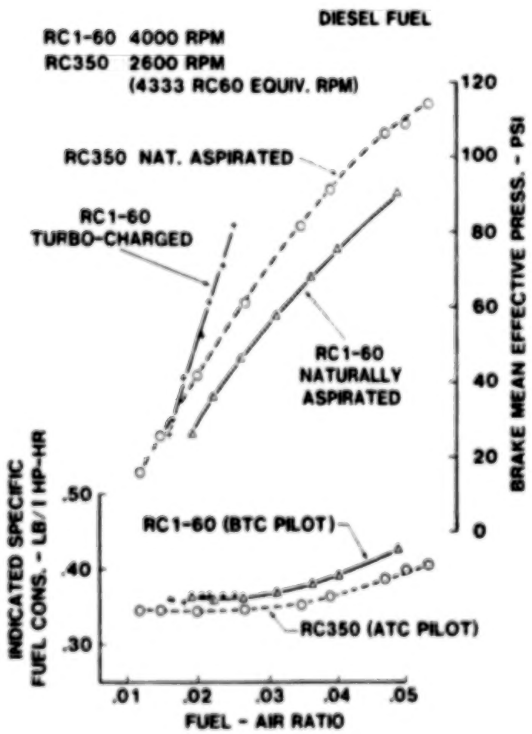


Figure 12.

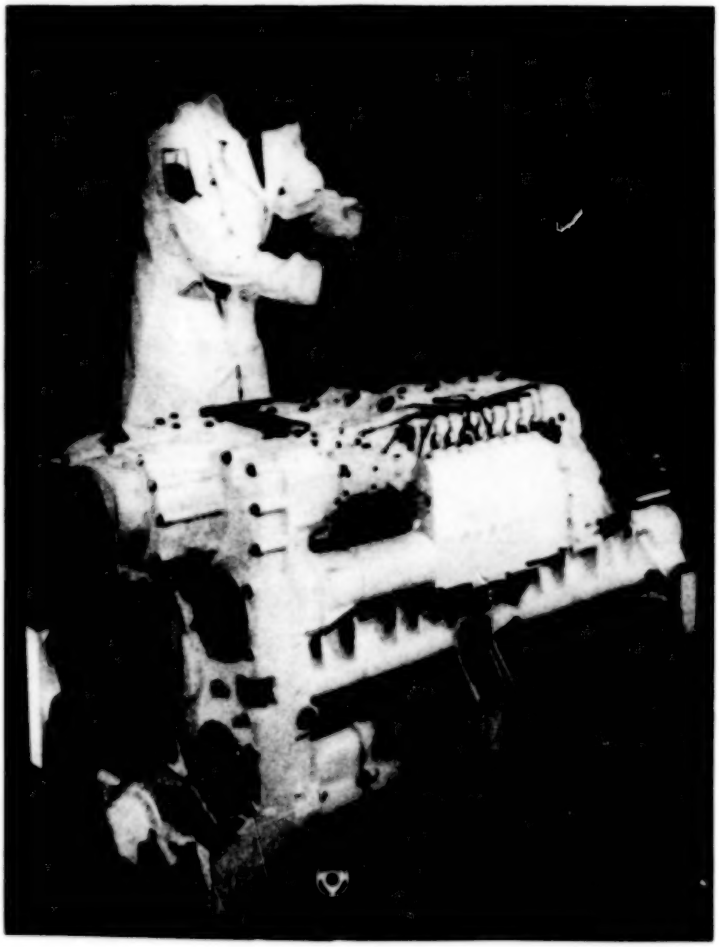


Figure 13.

RC4-350 engine

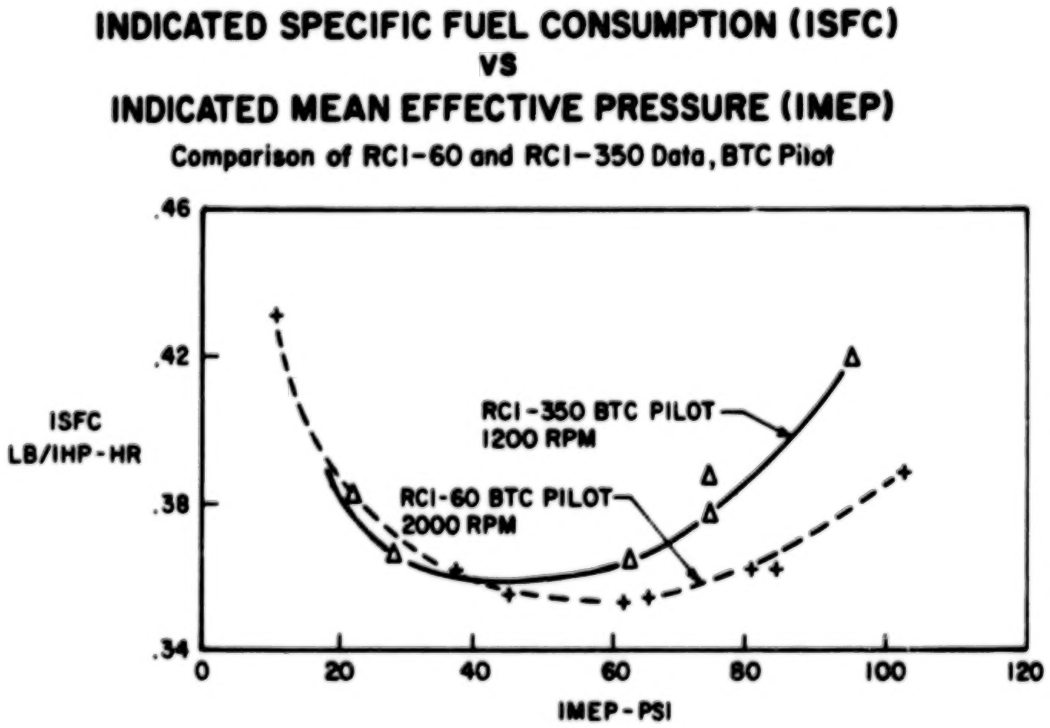


Figure 14.

BSFC vs BMEP, RCI-60 AND RCI-350

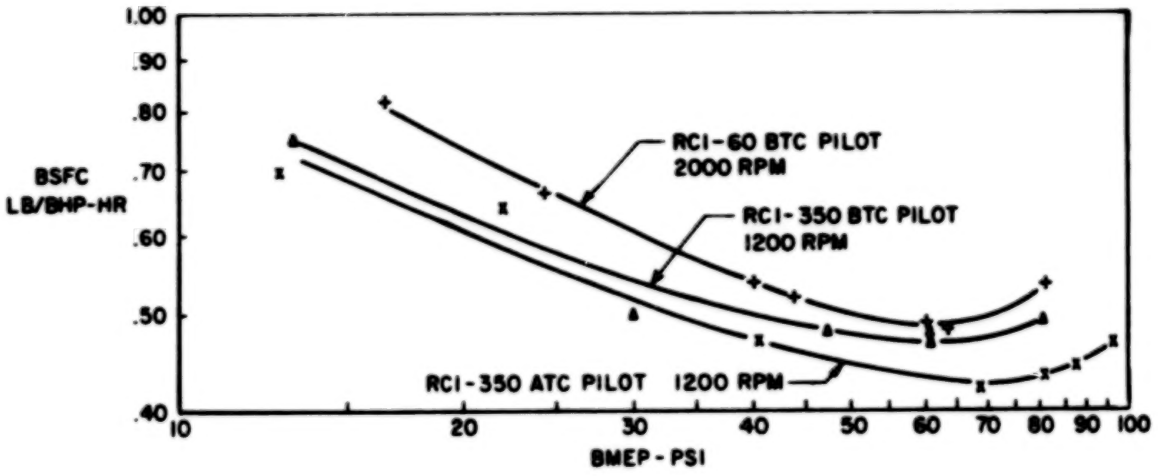


Figure 15.

NEW TECHNOLOGY SURVEY: CANDIDATE TECHNOLOGIES SELECTED FOR DESIGN STUDY

ADVANCED DESIGN

TURBOCHARGING

HIGH STRENGTH HIGH TEMPERATURE ALUMINUM CASTING ALLOY

LIGHTWEIGHT ROTOR

EXHAUST PORT THERMAL LINER

INDUCTION AIR INTERCOOLER

COUNTER-ROTATING PROPELLERS

ON-BOARD DIAGNOSTICS

IMPROVED APEX SEAL/TROCHOID MATERIAL COMBINATIONS

INCREASED IMEP AND SPEED

HIGHLY ADVANCED DESIGN

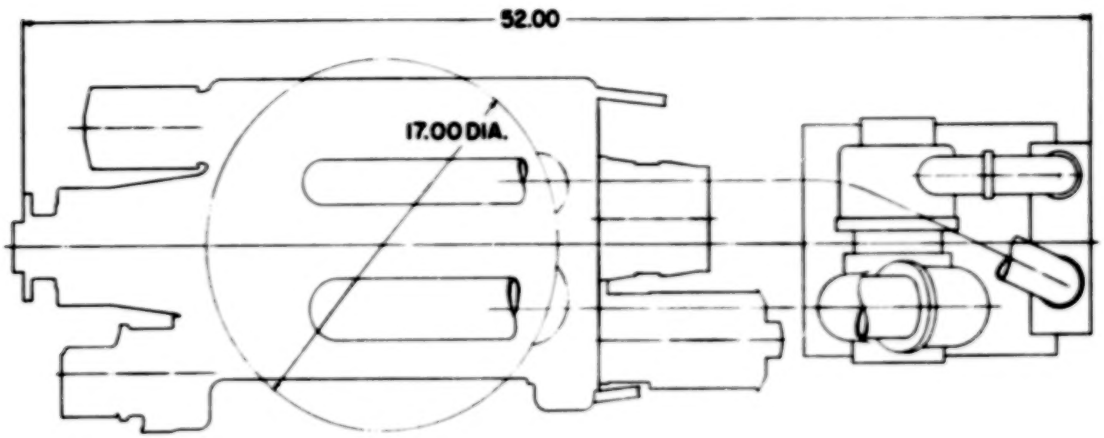
VARIABLE AREA TURBINE TURBOCHARGER

RETRACTING APEX SEALS

ROTOR COMBUSTION FLANK INSULATION

ADDITIONAL INCREASED IMEP AND RPM

Figure 16.



ADVANCED ROTARY COMBUSTION AIRCRAFT ENGINE
PRELIMINARY INSTALLATION STUDY
(250 BHP MAXIMUM CRUISE TO 25000 FEET)

Figure 17.

ADVANTAGES OF THE ROTARY STRATIFIED CHARGE AIRCRAFT ENGINE

MULTI-FUEL CAPABILITY
SMALL FRONTAL AREA
LOW ENGINE WEIGHT
REDUCED ENGINE COOLING AIR DRAG
IMPROVED RELIABILITY DUE TO FEWER PARTS
LOWER EXHAUST GAS TEMPERATURES
NO VALVES OR CAMS
SAFER CABIN HEAT
COOLANT COOLERS CAN BE WING DE-ICING
MORE RAPID FLIGHT DESCENTS PERMISSIBLE
LOW COST TURBOCHARGER FROM OTHER PRODUCTION RETAINED
SMALL EXHAUST AND INTAKE MANIFOLD VOLUMES BENEFIT TURBOCHARGING
LOW EXHAUST EMISSIONS
LOW FUEL CONSUMPTION
SMOOTH - BALANCED OPERATION
GOOD LOW TEMPERATURE STARTING CAPABILITY
LOW NOISE LEVEL
PROVEN PRODUCIBILITY OF ROTARY ENGINE

Figure 18.

LIGHTWEIGHT DIESEL AIRCRAFT ENGINES FOR GENERAL AVIATION

Steven G. Berenyi
Teledyne Continental Motors
General Products Division

Although we refer to it as a diesel engine, the compression-ignition engine runs well on Jet A, JP-5, and even on JP-4 with limitations because of cetane considerations. While this presentation is based strictly on our paper study, and describes the two engines indicated by the other speakers, I would like to point out that we have a single cylinder version of this engine running as of last week.

This study was initiated for Ed Willis' group. We looked at two different engines; one a far-out design and the other a less advanced one. What are the advantages of a diesel to general aviation? As we saw it, the incentives were reduced fuel consumption, reduced operating costs and reduced fire and explosion hazard. There are no ignition mixture control or inlet icing problems. There are fewer controls and no electrical interference problems.

Figure 1 is a schematic of the proposed engine. It has an independent turbocharger loop that can operate with its own starter, and has a combustor independent of the main engine. The engine itself has a radial configuration and employs the two-stroke cycle principle. The idea is to start up the turbocharger independently. This provides high pressure air in the lightweight engine which is designed to a maximum of 1500 psi firing pressure. Actually our engine design produces 1400 psi, with the balance of the pressure being made up by the independent turbocharger.

Why two stroke? Here are some of the advantages as we see them: weight reduction, fewer parts, improved reliability, and no valves. The absence of valves is a key advantage if we go to an uncooled, ceramic version, in which valves would present a problem in such an uncooled configuration. Further, the two stroke gives us reduced frontal area, particularly by eliminating the overhead valve mechanism and its associated frontal area.

Why uncooled? To go uncooled, we would have to go with ceramic piston tops and ceramic cylinder liners. These are pretty far out ideas for aircraft application at this point, but these are ideas that are being tried on engines for the Army right now (not airborne engines). Some of the cooling loss can be converted to useful energy, reducing cooling drag.

Why the independent turbo loop? Here are some of the features as we see them. The engine can be cranked indefinitely. As long as the turbo is running, it provides air and an assured start. There is plenty of high pressure (hot) compressed air for cold starting, and the turbo loop can be operated independently as an auxillary power unit (APU) when the main engine is not required.

Figure 2 shows a cutaway of the uncooled engine. No cylinder cooling is provided. Visible on the right at the rear of the engine are the combustor and turbo. Individual injectors are on the front. Figure 3a is a side view and Figure 3b is a frontal

projection. The engine is about 30 inches in diameter overall. The oil cooler and after cooler are below at the rear of the engines.

Our projections are that the cost is about 20% over that of a current aircraft engine of the same horsepower. Our weight projections are very favorable: 457 lbs. vs a comparable 578 lbs. The reason for this is the radial configuration which provides a compact engine with two main bearings. The crank case is very short and light.

Figure 4 is a comparison of operating characteristics of the diesel and a conventional six-cylinder gasoline engine. Figure 5 shows comparisons for BSFC on takeoff, full-power cruise and 65% cruise. These figures are for the uncooled ceramic version of the engine. Later on I will show some projections for the minicooled version in which cooling is provided in the combustion area only with no cooling lower on the base. Figure 6 is a dimension comparison with the 520 H gasoline engine. Results are favorable for the diesel. Figure 7 shows a comparison of dimensions for the two engines.

The installation study and airplane performance projections were made by Beech. Two comparisons were made of the computer-predicted airplane performance. One was for a fixed airplane with a variable performance (Figure 8A), and the other a fixed performance with variable airplane size (Figure 8B). Diesel characteristics are indicated by solid bars, and gasoline by stripes. The important points here are payload --1600 vs 1479, and range 1400 vs 932. In the second comparison (Figure 8B), we see that to fly the same range of 1400 nautical miles would take an airplane with a wing area of 322 square feet for the gasoline powered version vs 241 square feet for a diesel allowing a much smaller airplane of about 11,000 lbs. vs. 8000 lbs.

If we don't go with the totally uncooled version, what are alternate possibilities? One is limited cooling, where the combustion chamber only is cooled. The penalties with this design are increased fuel consumption, although it is still lower than current gasoline engines. If we eliminated the high speed alternator that would be associated with the APU type turbocharger, the conventional alternator would be employed. The penalties would be a larger, heavier alternator and larger batteries.

The engine for which hardware has been constructed is the 250 cruise horsepower engine with limited cooling and conventional materials. We have a single cylinder version which has been run up to about 25 horsepower in a "green" run. Our goal is 90 horsepower per cylinder for the takeoff rating. Projected BSFC of this particular engine would be 0.36 at cruise. The 250 horsepower engine combines the best features of the 400 and the 200 without the risk of introducing ceramics. It would be a low compression ratio radial engine, geared, two-stroke, four cylinder with the independent turbocharger. We would go with a conventional combustor with a high pressure turbocharger on the order of 8:1 pressure ratio.

This is one area where the NASA-sponsored turbocharger would work well. Although it is 8:1 on a single stage, it's not really that far out. We have turbochargers on other engines right now that are running 6:1.

If we project this engine program to the year 1995, or 2000, what are some things we could add to it? We could go to the high temperature materials; airbearings, plus turbocharging and turbocompounding. All would improve its performance.

The key technologies required to make this project successful are: the combustion and scavenging system in a two-cycle loop, and the high pressure, high efficiency

turbocharger. We do need a very high pressure injection system as well. And if we go to the independent turbocharger loop, we need the high speed starter/alternator. If we want to carry it further, we will need all of the above plus the ceramic components, advanced lubricant solids and airbearings.

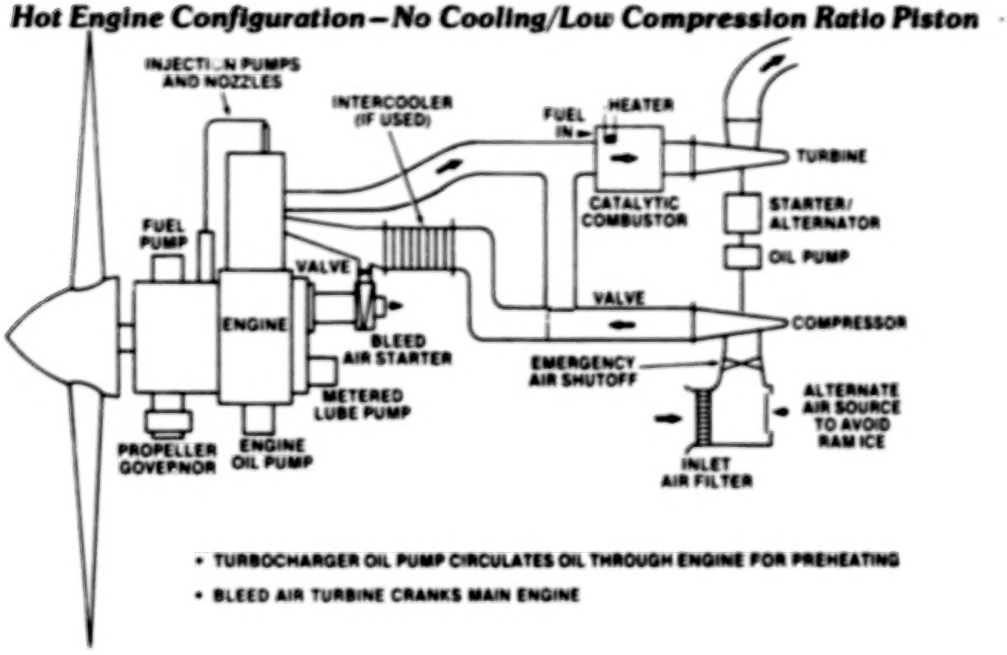


Figure 1.

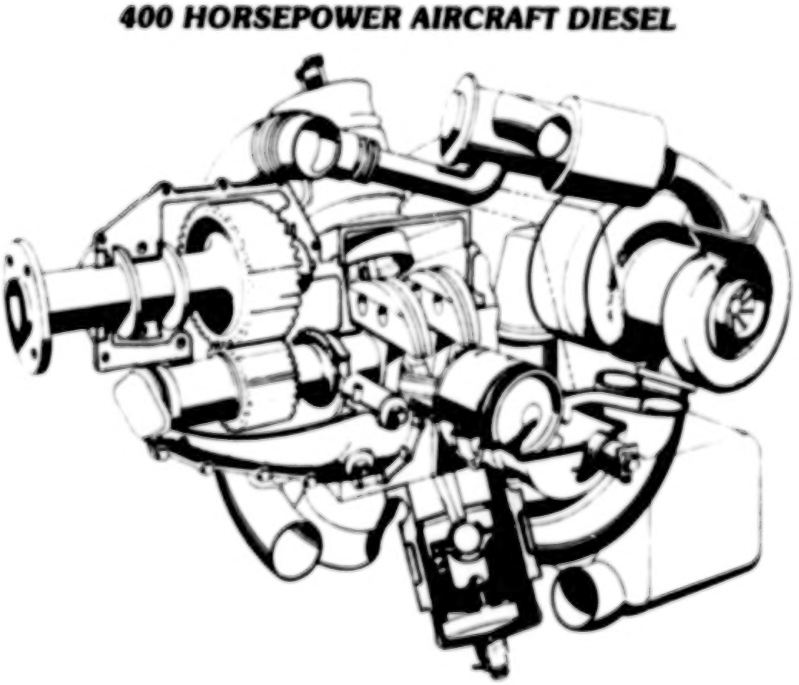


Figure 2.

400 HORSEPOWER AIRCRAFT DIESEL

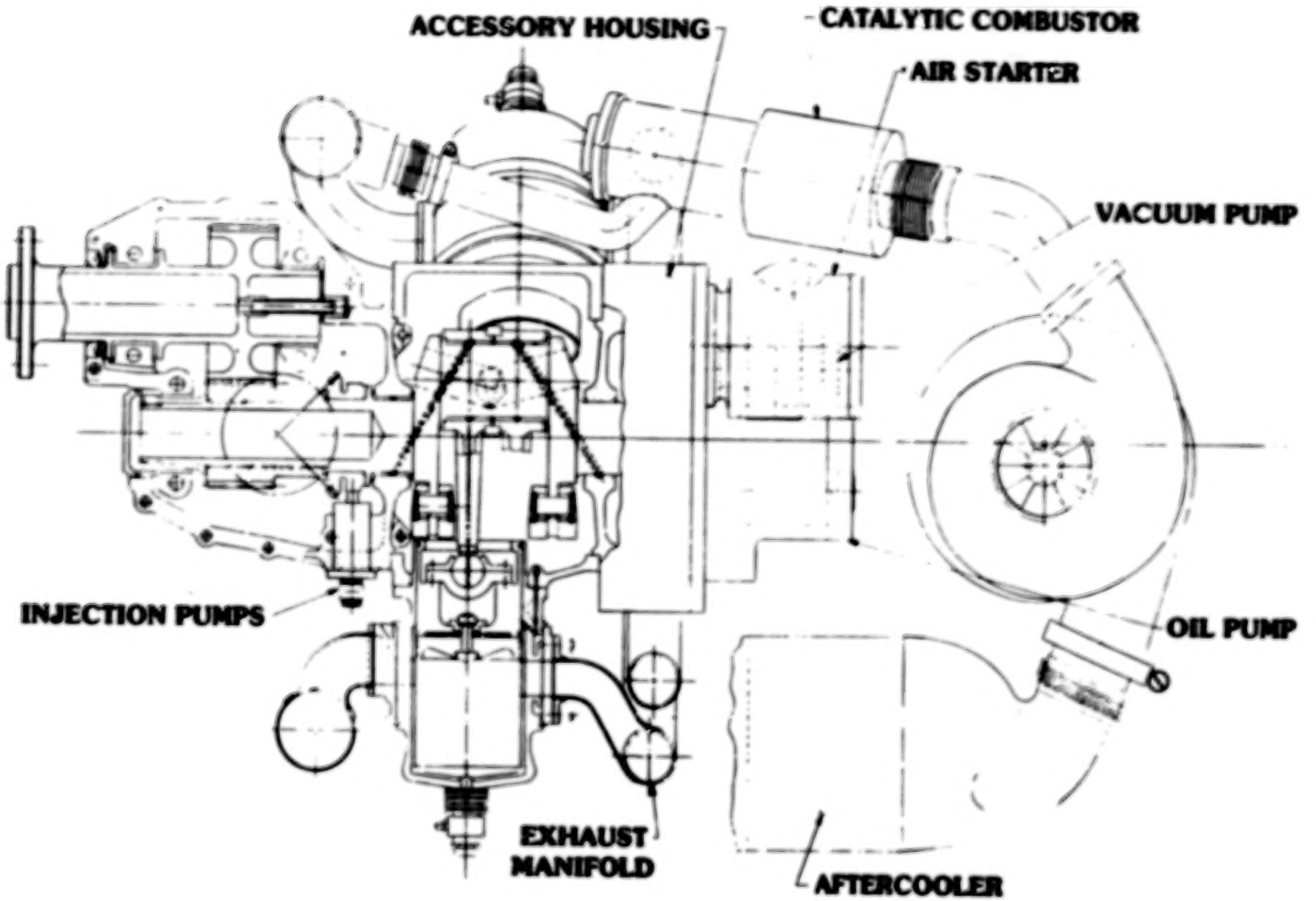


Figure 3a

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400 HORSEPOWER DIESEL AIRCRAFT ENGINE

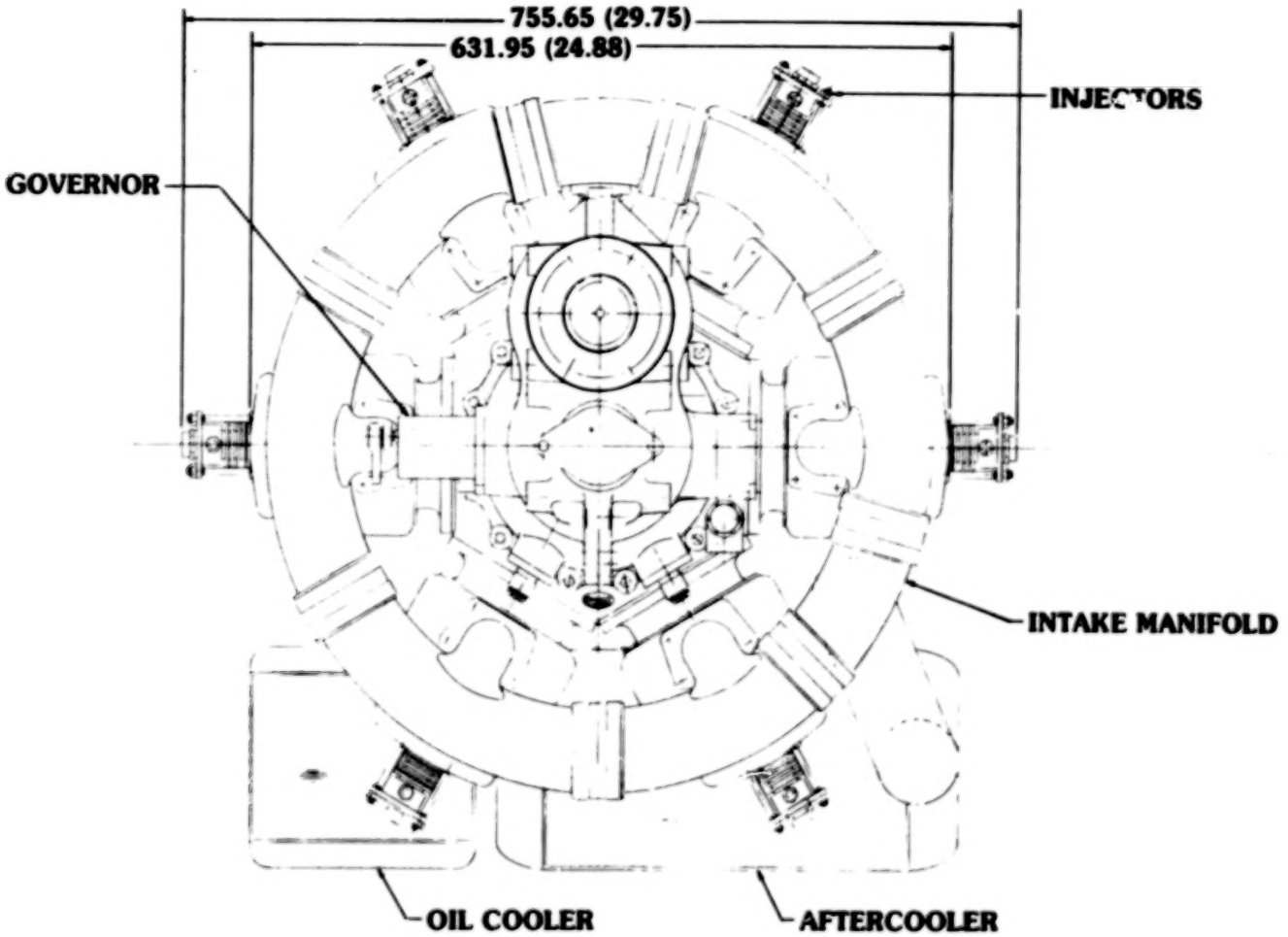


Figure 3b

COMPARISON GTSIO-520-H GASOLINE ENGINE AND GTDR-290 AIRCRAFT DIESEL

CONFIGURATION	GTSIO-520-H 6 CYL. OPPOSED	GTDR-290 6 CYL. RADIAL
DISPLACEMENT IN ^{3}	520	289
TAKE-OFF RPM	3400	3500
RATED MAX. TAKE-OFF HP	375	400
RATED MAX. FOR CRUISING	282	400

Figure 4.

COMPARISON GTSIO-520-H GASOLINE ENGINE AND GTDR-290 AIRCRAFT DIESEL

CONFIGURATION	GTSIO-520-H 6 CYL. OPPOSED	GTDR-290 6 CYL. RADIAL
BSFC LB/HP-HR:		
TAKE-OFF	.70	.37
FULL POWER CRUISE	–	.35
65% POWER CRUISE	.45	.32

Figure 5.

COMPARISON GTSIO-520-H GASOLINE ENGINE AND GTDR-290 AIRCRAFT DIESEL

CONFIGURATION	GTSIO-520-H 6 CYL. OPPOSED	GTDR-290 6 CYL. RADIAL
DIMENSIONS:		
LENGTH (INCHES)	64.25	43.50
WIDTH (INCHES)	34.04	24.88
HEIGHT (INCHES)	26.78	26.00
ENGINE WEIGHT DRY (LBS)	578	457

Figure 6.

SIZE COMPARISON GTSIO-520-H AND AIRCRAFT DIESEL GTDR-290 –400 BHP–

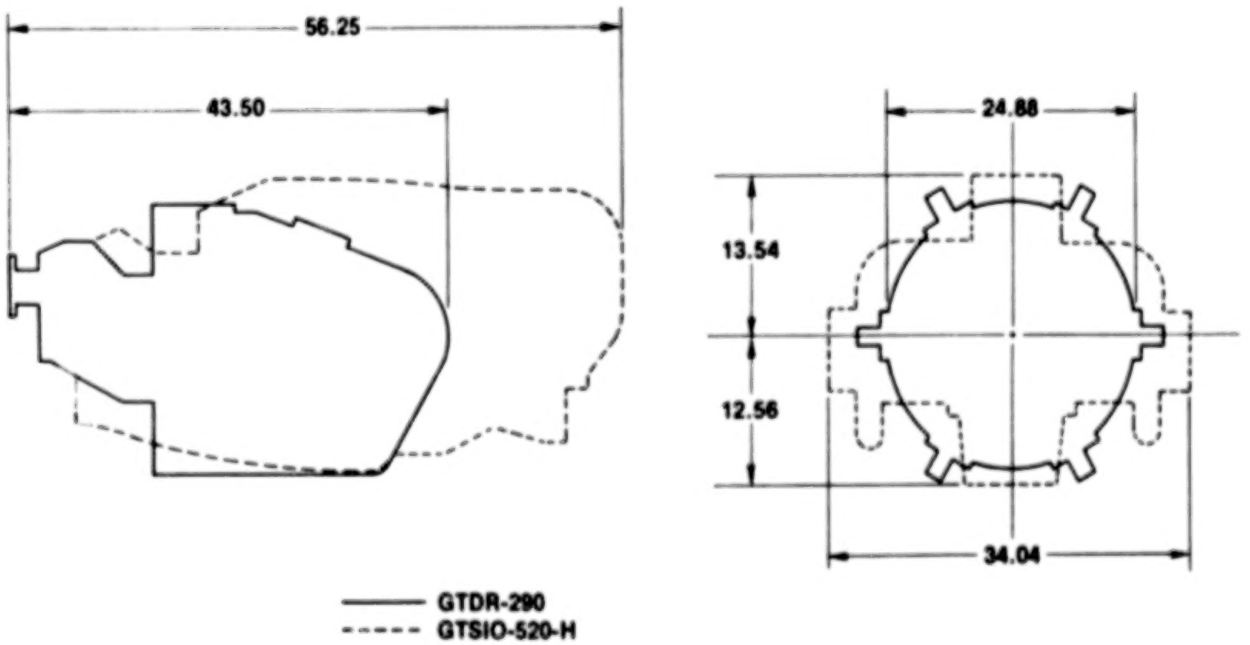
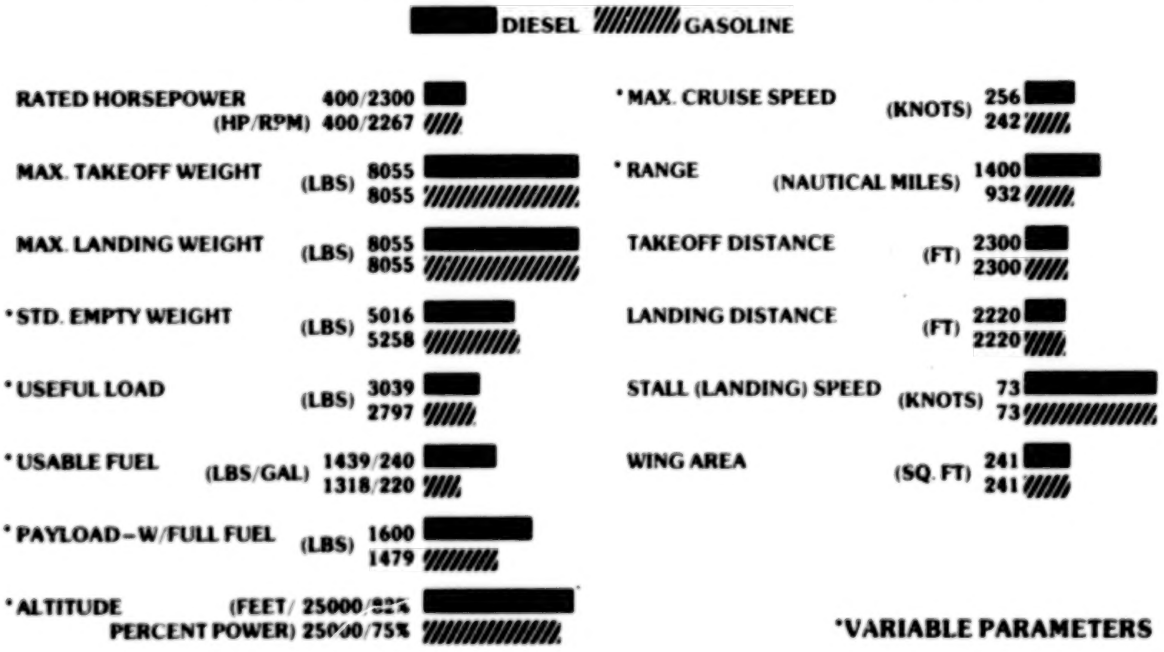


Figure 7.

COMPARISON
DIESEL AND GASOLINE POWERED AIRCRAFT ENGINES
400 HORSEPOWER • TWIN ENGINES

[A] FIXED AIRPLANE SIZE; VARIABLE PERFORMANCE


DIESEL
GASOLINE
RATED HORSEPOWER (HP/RPM) 400/2300 400/2267
MAX. TAKEOFF WEIGHT (LBS) 8055 8055
MAX. LANDING WEIGHT (LBS) 8055 8055
*STD. EMPTY WEIGHT (LBS) 5016 5258
*USEFUL LOAD (LBS) 3039 2797
*USABLE FUEL (LBS/GAL) 1439/240 1318/220
*PAYLOAD-W/FULL FUEL (LBS) 1600 1479
*ALTITUDE (FEET/PERCENT POWER) 25000/82% 25000/75%
*MAX. CRUISE SPEED (KNOTS) 256 242
*RANGE (NAUTICAL MILES) 1400 932
TAKEOFF DISTANCE (FT) 2300 2300
LANDING DISTANCE (FT) 2220 2220
STALL (LANDING) SPEED (KNOTS) 73 73
WING AREA (SQ. FT) 241 241
*VARIABLE PARAMETERS

[B] FIXED PERFORMANCE; VARIABLE AIRPLANE SIZE

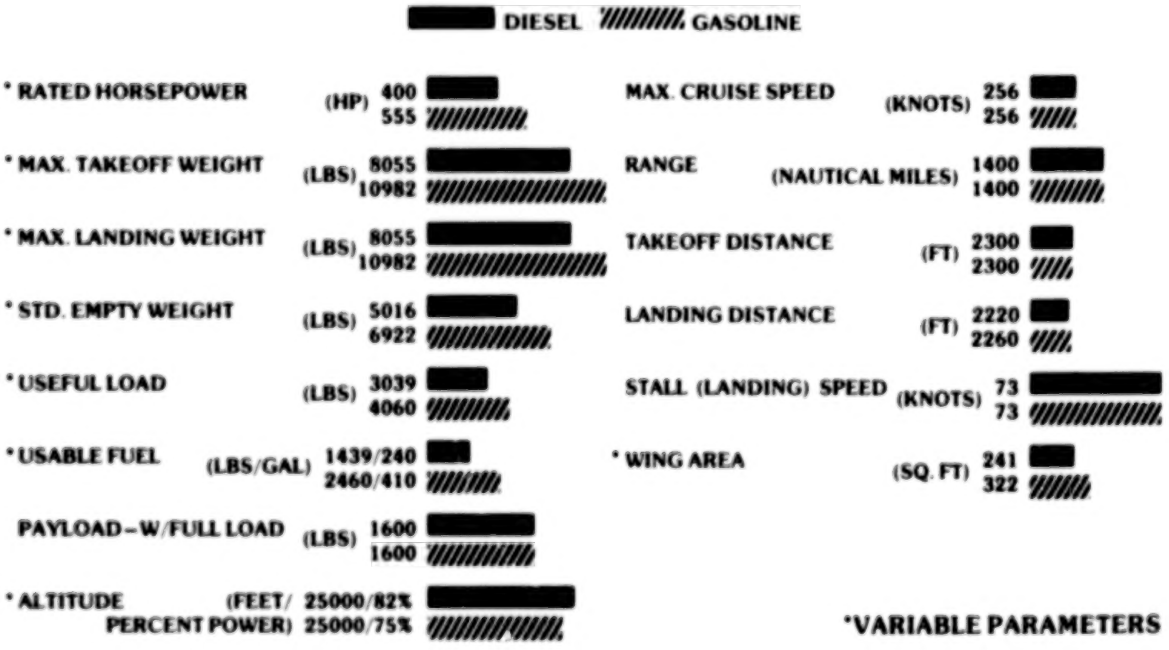

DIESEL
GASOLINE
*RATED HORSEPOWER (HP) 400 555
*MAX. TAKEOFF WEIGHT (LBS) 8055 10982
*MAX. LANDING WEIGHT (LBS) 8055 10982
*STD. EMPTY WEIGHT (LBS) 5016 6922
*USEFUL LOAD (LBS) 3039 4060
*USABLE FUEL (LBS/GAL) 1439/240 2460/410
PAYLOAD-W/FULL LOAD (LBS) 1600 1600
*ALTITUDE (FEET/PERCENT POWER) 25000/82% 25000/75%
MAX. CRUISE SPEED (KNOTS) 256 256
RANGE (NAUTICAL MILES) 1400 1400
TAKEOFF DISTANCE (FT) 2300 2300
LANDING DISTANCE (FT) 2220 2260
STALL (LANDING) SPEED (KNOTS) 73 73
*WING AREA (SQ. FT) 241 322
*VARIABLE PARAMETERS

Figure 8.

AN OVERVIEW OF GENERAL AVIATION PROPULSION RESEARCH PROGRAMS AT NASA LEWIS RESEARCH CENTER

Edward A. Willis
NASA Lewis Research Center

INTRODUCTION

At NASA Lewis, we have been involved for several years with studies and limited in-house and contract experimental research on intermittent combustion (I.C.) engines. These come in a great variety of different structural forms; but they all use the same basic combustion cycle. This is evolving into a hybrid diesel/otto type cycle, which is termed "stratified-charge." There are several reasons why this class of engines is of such widespread application and utility in the transportation field, which includes several things besides general aviation. In brief, they are efficient, inexpensive, fuel-tolerant and load-flexible; they have very good off-design efficiency.

Figure 1 shows NASA's perceptions of the general aviation (G/A) industry's major needs and concerns. Notice that exhaust emissions is not included. The program was originally oriented towards emissions when it was established in 1975, under a regulatory threat and at the request of the OMB. The standards, however, were not put into effect, and the program was redirected to emphasize energy efficiency. This is one of the industry's major concerns, and that is the reason why we are having this workshop.

Everybody here has heard the horror stories about what is happening to avgas prices and supplies, and many have experienced this personally. Evidently, the situation is even worse abroad than it is here. Everything being done in our I.C. engine research program is aimed, directly or indirectly, at either producing the technology for advanced conventional-type engines which will burn less avgas, or producing technology for all-new alternative engines which could burn a more available fuel at high efficiency. Our program has three main parts. Here and in the handout paper, these are labeled as "Piston Engine Technology," "Alternative Engines," and "Combustion Diagnostics and Modeling." I will discuss each one individually, but emphasizing the "Alternative Engines" area because it has the major implications as to what kind of fuel can be used.

Several overall highlights deserve mention before we attempt to cover the three specific areas. TCM has completed a contract effort showing that a few well-chosen and fairly simple modifications can produce substantial improvements in a current-production type engine. We have started a grant effort with Princeton on a fuel

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*The remarks of Dr. Willis were intended to be a summary of the more detailed report, "An Overview of General Aviation Propulsion Research Programs at NASA Lewis Research Center," NASA TM 81666, April 1981. A copy was provided to each workshop attendee.

management control system. In addition, we have completed in-house studies to evaluate and compare the alternative engines that were delineated in Session #3. The studies indicate substantial reductions in the size and weight of an airplane are possible if it were redesigned around the new engine. Many of these engine concepts offer very large reductions in mission fuel burned and the ability to burn fuels other than present-day avgas, such as jet fuel or diesel fuel. Looking towards higher horsepower applications, we have recently initiated studies on the application of diesel and rotary engines for commuter type aircraft.

In the in-house area, we have completed baseline testing for both diesel and rotary engine programs. We also initiated some new efforts in several other areas such as a high altitude turbocharger study and, of course, this workshop. Looking to the future, we are now planning an in-house program on stratified charge combustion research.

Earlier in the year we completed a planning and advocating exercise for considerably expanded programs involving several kinds of I.C. engines.

PISTON ENGINE TECHNOLOGY

Our piston engine program has evolved from the original, emissions-oriented program that began in 1975. It was redirected to emphasize gasoline economy in 1978. It is somewhat near-term oriented and involves technology which could be applied to the kinds of engines that are currently in production, without disrupting existing production facilities and processes. Generally, we are pursuing this through various approaches to lean-burn gasoline combustion, together with related things that are required. Figure 2 shows a status summary of our piston engine technology program. To date, we have finished a contract program with TCM which offered worthwhile improvements in fuel economy. Moreover, it showed a great reduction in exhaust emissions which was the original purpose of the program. In this program, four relatively simple concepts were combined, namely, an improved fuel injection system, variable spark timing, spot-cooling air injection, and a thermal barrier liner in the exhaust port. The latter has a narrow gap between the liner and the metal of the cylinder head which was purged with the spot cooling air. Ultimately, this air passes around the valve stem and cools that area. These design features are shown in Figure 3.

The tabulated data in Figure 3 summarizes the most significant results of the program. First, consider the emissions. These are listed as percentages of the EPA standards that were proposed at one time. The original engine was 185% on CO, meaning 85% over the standard. At the end of this work, it was only 45% of the standard, so there was an improvement by a factor of four. We had a considerably larger improvement in the hydrocarbon emissions. The NO_x did go up, but it was still well within the standard.

More significant in today's scenario were the reductions in mission fuel. Depending on the baseline chosen, these would amount to as much as 30% for the landing and takeoff cycle, and about 10% for the high-power 75% power cruise mode. This effort is completed now, except for a flight demonstration of the engine which ought to take place soon. We feel it has been a very successful example of cooperation between NASA and a G/A manufacturer, and a precedent that should be followed for the future.

COMBUSTION DIAGNOSTICS AND MODELING

There is not time to try to cover our combustion diagnostic research in detail. Figure 4 gives the basic objective and approach, including instrumentation items. Considerably more detail can be found in the handout report. Let us consider some of the instrumentation developments. In recent years, we have developed real time, IMEP instrumentation for piston-type engines. Most recently, that has now been extended to rotary engines and validated in our in-house test program. Harold Schock is going to give a paper on that at the SAE national meeting later this month in Detroit. We have also developed other real time instrumentation that gives us the mass fraction burned curve. This is a very important measure of how the combustion process is proceeding inside the cylinder. We have also developed and used ionization probes to track the progress of the flame front across the combustion chamber.

Last year we had some success with a sampling valve and mass spectroscope system which can determine the chemical composition of gases in the cylinder at a particular point in the cylinder and at a particular time in the cycle. This enables us to get a much better understanding of the basic chemistry and kinetics in the cylinder.

Now work is underway with a Laser Doppler Velocimeter system (LDV), to determine velocity and turbulence patterns in the internal flow passages of the engine. We had a small amount of precursory LDV work done under a grant to Carnegie Mellon University. This was to help validate a two-dimensional I.C. engine cycle model program that they are developing for us. Our in-house LDV work is growing. A test cell for the work has been identified and some equipment is on hand already.

ALTERNATIVE ENGINES

Let us now turn to a discussion of our alternative propulsion systems program. The objectives are shown in Figure 5. Originally, we were looking for improvements in fuel consumption of 30% to 50%. Results now indicate that in the best cases, improvements may exceed 50%.

The amount of money that was devoted to the alternative engine area in the previous couple of years is about $350K/year, which is roughly half of our "outside" budget. The objectives for 1980/81 were to complete the design studies and airplane mission evaluations and define the technology needs of these advanced engines: in 1981, to be able to select on a logical basis one or more candidates for augmented or intensified programs; and, hopefully, in 1982 to initiate a considerably expanded program dealing with the selected candidate(s).

Figures 6 through 14 illustrate the results of the alternative engine studies. These engines were described in Session #3, so I am not going to dwell on them again. The history of that part of the program is as follows. About two years ago, the "GATE" studies on highly advanced, small turboprops were completed. They were well publicized and the results looked pretty good. About one year ago, we finished up the major part of the study on the two-stroke cycle diesel. It looked good too. More recently, we completed the study on two versions of the four-stroke cycle piston engine. This was a study done by Teledyne Continental. The final report is now out. The rotary study is not quite complete, but hopefully it soon will be.

In any case, they are all far enough along to have already generated some comparative performance results. First, there was a series of in-house studies that were performed by Bill Strack's group and which were reported in a NASA report published last November. Contracts with Beech and Cessna are underway now to perform a more detailed study of two of the same airplanes and missions that Bill Strack and his group included among a larger number. The intent was to make sure that the NASA results are realistic, and also to get the industry's participation in evaluating the potential of all four engine concepts.

A limited amount of supporting technology work has been going on for each of the I.C. engines. I mentioned earlier that our rotary and diesel test cells are operational. We completed a contract program with Curtiss Wright that showed a substantial improvement in the BSFC of the existing gasoline rotary engine that they had built about ten years ago. This was a ten-year-old design; but we did show about a 15 or 18% improvement in BSFC without major changes. I mentioned that our single cylinder lean-burn test cell is currently in an operational status. We are now running baseline data on the test engine as received. We will then test two different lean-burn combustion concepts. After that, we will hopefully be able to move into the full stratified charge area using jet fuel as the fuel of choice.

We have had a diesel single-cylinder test engine patterned after the two-stroke diesel study under construction for about the past year. It is now built and the acceptance test procedures are underway. Everything has been finished except one final test where the NASA manager has to go there and physically watch the engine run. Now there is finally, at long last, a testbed available with which to develop and verify new technology for an advanced, two-stroke aircraft type diesel engine.

Figure 15 summarizes some results of the mission and comparative performance studies on two airplanes. Shown are weight savings in terms of either mission fuel or takeoff gross weight. These are rough measures of the cost of buying and flying the airplane. We picked three engines as being representative of the extremes that were covered within the study. The GATE turboprop was selected because it was lighter than any of the other engines and yet it was not quite as efficient in terms of specific fuel consumption. The spark ignited engine (S.I.) selected was the moderate risk gasoline lean-burn engine that Ken Stuckas discussed in Session #3. The lightweight diesel was the higher risk (not ceramic) version of the diesel engine that was described by Stephen Berenyi in Session #3 as a 1992 possibility. The diesel results are also representative of what could be done with the stratified charge piston engine or rotary engine since we found relatively small differences between the three. In the discussion below, these three engines are termed the "diesel group."

Starting at the left of Figure 15, we first look at the fuel savings on a six-passenger, single airplane which had about a 250-knot cruise speed and about 1,000 miles range. The fuel savings ranged from a little over 30%, for the GATE engine and the moderate risk or gasoline powered recip engine, up to about 45% or a little over for the higher risk diesel group of engines. In terms of the gross weight of the airplane, both the GATE turboprop and the advanced diesel group showed a 25% to 30% savings, which we think is impressive. Even the moderate risk gasoline engine showed about a 15% saving, which is very encouraging considering the probable lower cost involved in actually coming up with such an engine.

The story was similar with the twin engine, except that the diesel group seemed to have a bigger edge in terms of reducing fuel consumption. However, the advantages in terms of gross weight came out about the same. It should be pointed out that the weight

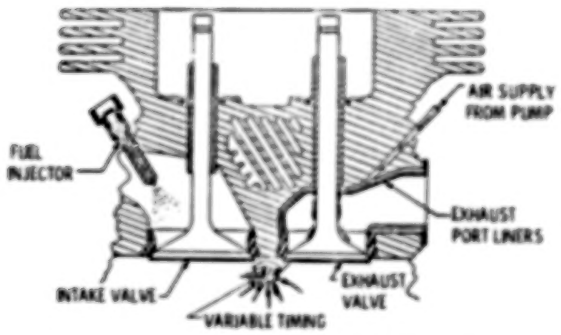
savings comparison is for different fuels; i.e., pounds of gasoline versus pounds of jet fuel. Converted to gallons, the weight savings of about 45% for the diesel group is more like 55% in terms of gallons, and perhaps 60% in terms of the actual cost of the fuel. In conclusion, let me refer you to the handout, NASA TM 81666, for more details of the current NASA Lewis programs.

- o IMPROVED SAFETY (PRODUCT LIABILITY)
- o IMPROVED AIR TRAFFIC CONTROL
- o IMPROVED ENERGY EFFICIENCY (SURVIVAL ISSUE)
- o PROPULSION TECHNOLOGY A KEY AREA - SPECIFIC NEEDS
  - REDUCED FUEL CONSUMPTION, WEIGHT & DRAG
  - MULTIFUEL CAPABILITY (AVGAS & JET/DIESEL)
  - BETTER RELIABILITY, DURABILITY, MAINTAINABILITY, FEWER FAILURE MODES
  - NEAR TERM & LONG TERM TECHNOLOGY

Figure 1. - General Aviation industry - needs/concerns.

- o NEAR TERM IMPROVEMENTS -- TEST ENGINE INTEGRATING THE 4 MODS MET THE EMISSION STANDARDS AND DEMONSTRATED 10-11% IMPROVEMENT IN HIGH-PERFORMANCE CRUISE FUEL ECONOMY, 30% IMPROVEMENT OVER LTO CYCLE, FLIGHT DEMO PLANNED FY 81
- o COOLING -- TCM CONTRACT UNDERWAY, CSD MANPOWER COMMITTED
- o FUEL INJECTION -- TECHNICAL EFFORT COMPLETE ON SPECTRON SPRAY CHARACTERIZATION CONTRACT.
  -- IN-HOUSE FLOW VISUALIZATION FACILITY OPERATIONAL, INITIAL RESULTS GENERATED.
- o ADV. TURBOCHARGER -- STUDY CONTRACT BEING NEGOTIATED
- o AVGAS WORKSHOP -- PLANS FIRMED UP FOR FEBRUARY 3, 4, & 5, 1981

Figure 2. - Piston engine technology - status summary.



EMISSIONS	PRODUCTION ENG.	MODIFIED ENG.
CO% EPA STD.	182	20
HC% EPA STD.	127	1
NOx% EPA STD.	10	70
30% FUEL SAVINGS ON LTO CYCLE		
10% FUEL SAVINGS IN 75% POWER CRUISE MODE		

Figure 3. - Concept integration.

OBJECTIVE: DEVELOP COMBUSTION DIAGNOSTIC CAPABILITIES AND PREDICTIVE COMBUSTION/CYCLE PERFORMANCE MODELS FOR SCIENTIFIC I.C.E. DESIGN

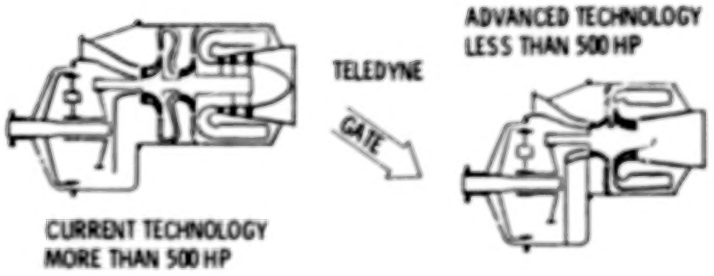
APPROACH:
- o COMPUTER MODELING OF I.C.E. COMBUSTION AND FLOW PROCESSES
  - RAPID APPROXIMATE CODES FOR STUDY
  - DETAILED MULTIDIMENSIONAL CODE FOR DESIGN
- o EXPERIMENTAL VALIDATION/REFINEMENT OF ABOVE
- o DEVELOPMENT AND UPGRADING OF FACILITIES AND INSTRUMENTATION
- o COMBUSTION DIAGNOSTIC INSTRUMENTATION
  - REAL TIME IMEP, MASS FRACTION BURNED
  - IONIZATION PROBES
  - SAMPLING VALVE/MASS SPECTROSCOPY
  - LASER DOPPLER VELOCIMETRY (LDV)
  - LASER/INFRARED SPECTROSCOPY

Figure 4. - Combustion diagnostics and modeling.

OBJECTIVE: ESTABLISH THE TECHNOLOGY BASE FOR ADVANCED IC ENGINES WHICH HAVE 30% - 50% REDUCED FUEL CONSUMPTION, LOW EMISSIONS, AND BROAD-SPEC. FUEL CAPABILITY

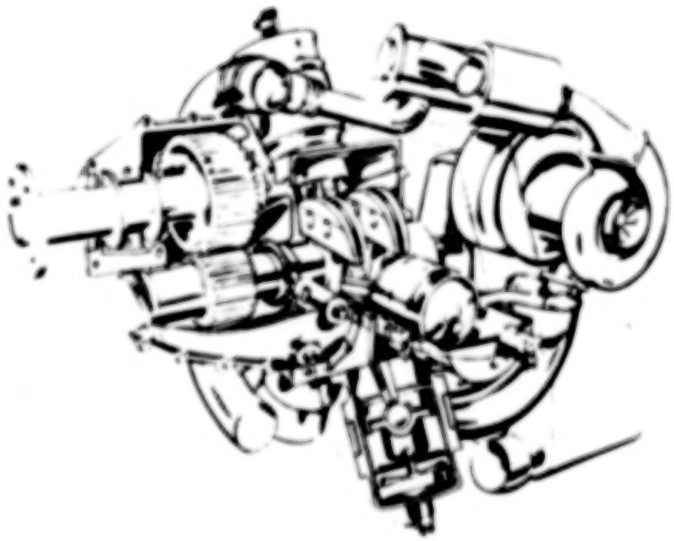
TARGETS:
- o (1980) COMPLETE ALTERNATIVE ENGINE DESIGN STUDIES AND AIRPLANE/MISSION EVALUATIONS AND DEFINE TECHNOLOGY NEEDS
- o (1981) SELECT ONE OR MORE CANDIDATE(S) FOR 1982 AUGMENTED PROGRAMS
- o (CONTINUING) SUPPORTING TECHNOLOGY INVESTIGATIONS
- o (1982) INITIATE AUGMENTED ENGINE TECHNOLOGY ENABLEMENT PROGRAMS

Figure 5. - Alternative propulsion systems.



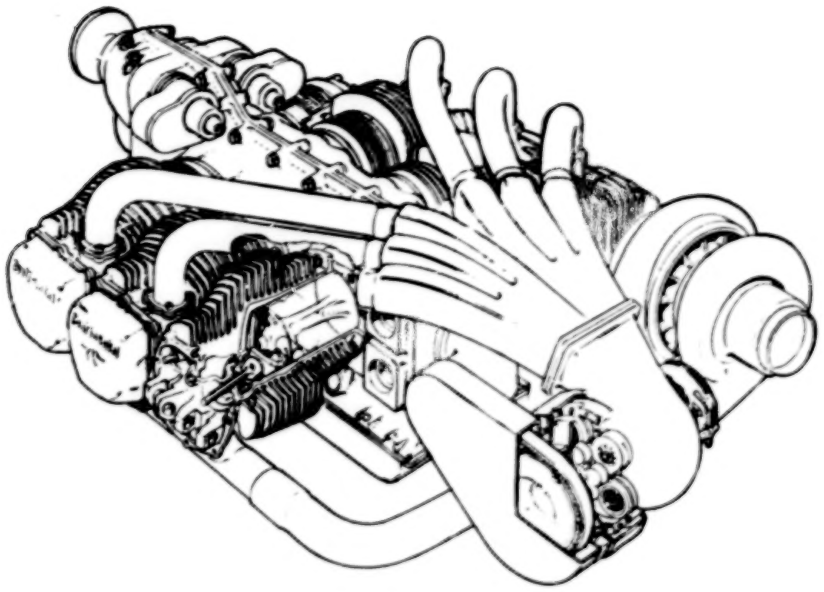
	ENGINE COST SAVINGS	
2 CENTRIFUGAL COMPRESSORS	10%	1 CENTRIF. COMPRESSOR
3 AXIAL TURBINES	16%	1 RADIAL TURBINE
HYDROMECHANICAL CONTROLS	12%	ELECTRONIC CONTROL
ATOMIZING COMBUSTOR	2%	VAPORIZING PLATE COMB.
8-1/2 PR/1900° F CYCLE	9%	9.0 PR/2250° F CYCLE
	49%	

Figure 6. - Advanced technology investment reduces engine price.



	ADVANCED VERSION	NEARER-TERM VERSION	
CRUISE BSFC	0.32	0.37	LBS/BHP-HR
SPECIFIC WEIGHT	1.02	1.14	LBS/TOHP

Figure 7. - Lightweight diesel aircraft engine study.



	ADVANCED VERSION	NEARER-TERM VERSION
CRUISE BSFC	0.33	0.36 LBS/BHP-HR
SPECIFIC WEIGHT	1.16	1.39 LBS/TOHP

Figure 8. - Artist's conception of hign risk technology engine.

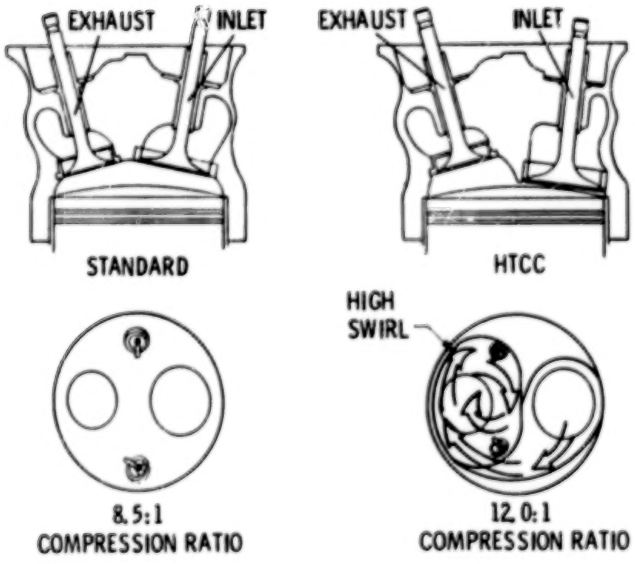


Figure 9. - High compression ratio/lean burn combustion chamber.

	CURRENT TECHNOLOGY TSIO-550	PERCENT IMPROVEMENT	MODERATE-RISK TECHNOLOGY GTSIO-420	PERCENT IMPROVEMENT	HIGH-RISK TECHNOLOGY GTSIO-420/SC
CONFIGURATION ENGINE DISPLACEMENT	6-Cylinder/Horiz. Opposed 550 Cubic Inches	—	6-Cylinder/Horiz. Opposed 420 Cubic Inches	—	6-Cylinder/Horiz. Opposed 420 Cubic Inches
MAXIMUM RATED POWER/SPEED	350 Bhp/2,800 rpm	—	350 Bhp/3,200 rpm	—	350 Bhp/3,200 rpm
BRAKE SPECIFIC FUEL CONSUMPTION AT MAXIMUM CRUISE POWER (250 Bhp)	0.446 lb/Bhp-hr	20%	0.358 lb/Bhp-hr	26%	0.331 lb/Bhp-hr
SERVICE CEILING	25,000 ft	40%	35,000 ft	40%	35,000 ft
INSTALLED ENGINE WEIGHT	585 lb	17%	486 lb	31%	486 lb
TYPE OF FUEL	100 Octane	—	100 Octane	—	Jet A
TIME BETWEEN OVERHAUL	1,400 hr	43%	2,000 hr	43%	2,000 hr
EXHAUST ENERGY RECOVERY SYSTEM	Turbocharging	—	Turbocharging Turbocompounding	—	Turbocharging Turbocompounding
EXHAUST POWER UNRECOVERED AT MAXIMUM CRUISE POWER	319 hp	33%	214 hp	51%	156 hp

Figure 10. - Engine specification comparison.

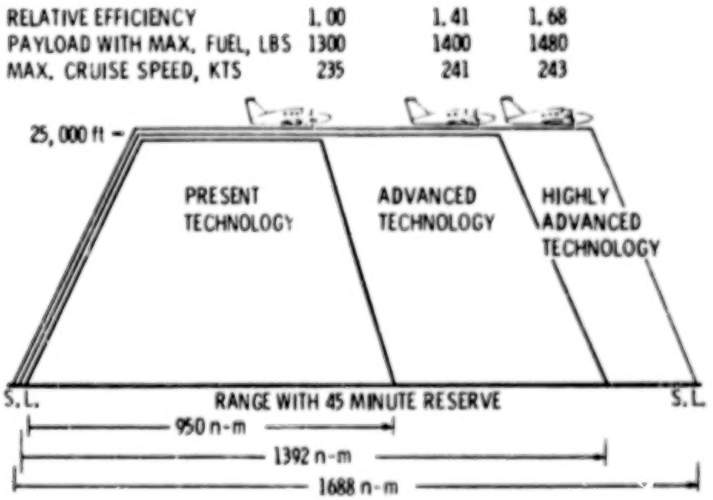


Figure 11. - Advanced technology twin-engine airplane.

	ADVANCED VERSION	NEARER-TERM VERSION	
CRUISE BSFC	0.35	0.37	LBS/BHP-HR
SPECIFIC WEIGHT	0.80	1.09	LBS/TOHP

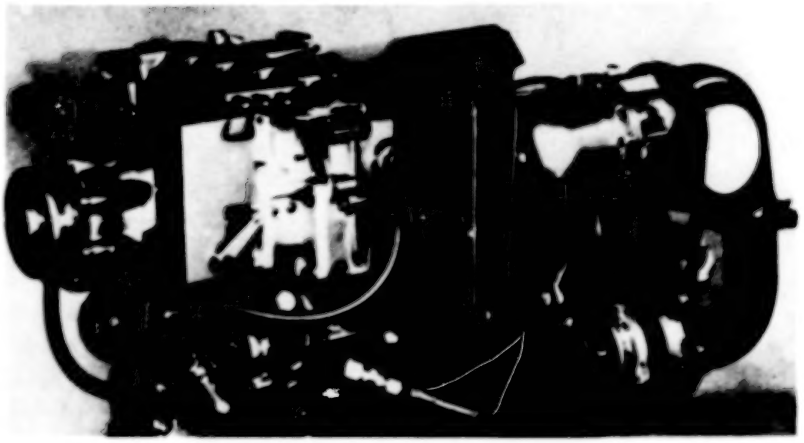


Figure 12. - Multifuel rotary engine study.

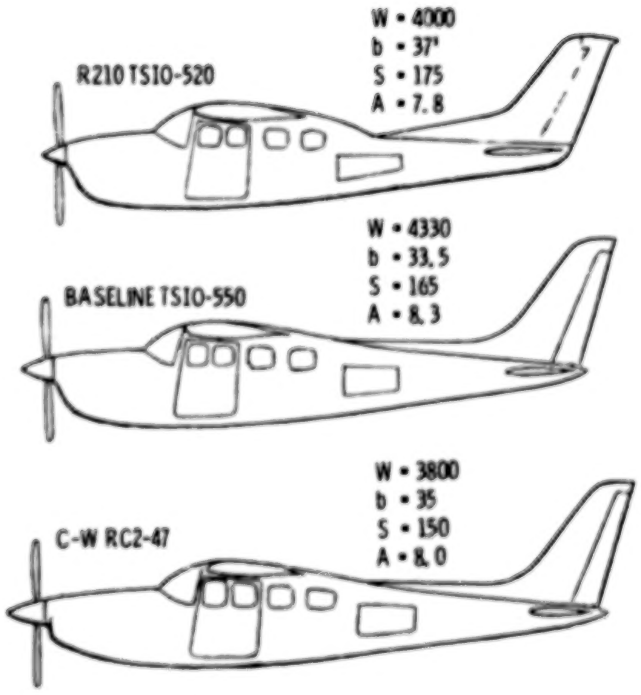


Figure 13. - Airplane/engine comparisons.

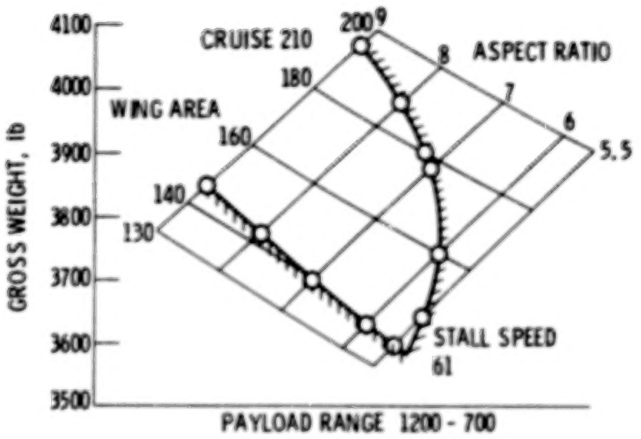


Figure 14. - Airplane sizing with Curtiss-Wright single engine RC2-47. Takeoff and climb performance exceeds constraint values for all design points.

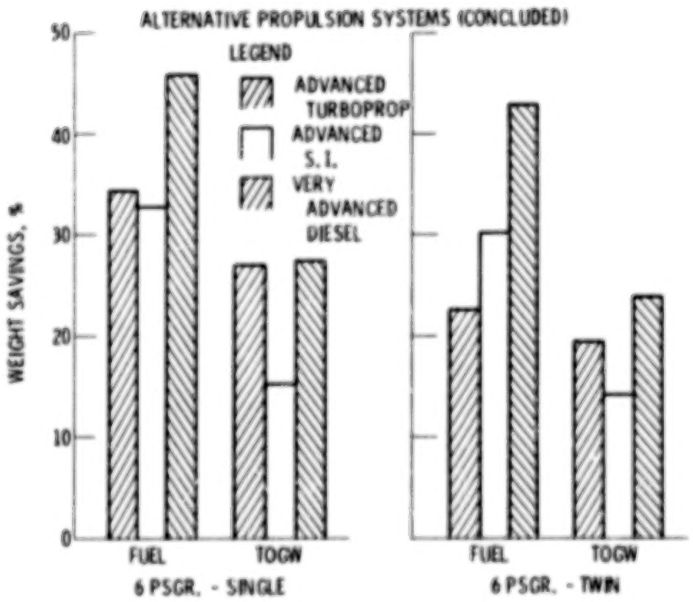


Figure 15 - Fuel and airplane weight savings with advanced turboprop and diesel powerplants in future GA airplanes (25 000 cruise - 250 KT, 1000 - 1600 MI range).

GENERAL AVIATION TURBINE ENGINE (GATE) OVERVIEW

William C. Strack
NASA Lewis Research Center

Previous papers have mentioned various alternative powerplants that could be considered for future aviation use; among these, the turboprop (TP). While turboprops should not be the major part of this workshop, for completeness I will summarize the content of the GATE turboprop studies that were completed two years ago. Those studies were initiated not with the intent of supplanting some of the reciprocating powerplants that we have today but rather of defining the best opportunity for small turbine power plants. The GATE studies suggested that the 300-600 horsepower range was best for small turboprop engines.

As everyone knows, turbine powerplants are conventional in the large aircraft arena and, unlike the other engine candidates, the challenge is to develop fuel-efficient small ones at reciprocating engine prices. While some advantages (e.g., reliability, low maintenance, vibration-free operation, jet fuel) are relatively easily realized, engine cost and fuel inefficiency are problems. The main theme, then, of the GATE studies was one of reducing the manufacturing costs of small turbine engines without sacrificing the advantages.

Figure 1 shows the approaches that were investigated by the four study teams involved. Mainly they chose to simplify the engine: one rather than two centrifugal compressors, and one radial turbine rather than three turbine stages.

Another approach involved new manufacturing technology; ways of manufacturing small parts that are reasonably accurate and yield reasonable performance (not ultimate performance) but are substantially lower in cost. An example is making almost finished parts in one piece using powder metal techniques. The compressor might be manufactured that way. Another example is making small, cooled radial turbines with laminated sheets of super-alloy, powdered material, that have the cooling holes photo-etched into them.

When all the technology studies were done and the accompanying market analyses were complete, the conclusion was that it is indeed possible to reduce the cost of turbine engines by a factor of 3 using low-cost manufacturing techniques and increased production rates. In the interest of reducing engine cost, some performance was sacrificed. Yet we ended up with about a 20 percent predicted improvement in SFC over current technology turboprops. However, even this level of improvement does not match the low SFC of reciprocating powerplants--particularly those advanced concepts described earlier. The 20 percent better SFC and much lower weight of a turboprop does mean that if such a powerplant were installed in a resized small airplane, one could save between 10 and 30 percent fuel relative to existing recip engines, depending on different mission and airplane combinations. This is shown in Figure 2. The price of the aircraft would go down about 15 percent in the case of a high powered single, or 25 percent in the case of a normal size twin. The operating costs would decrease about 10 percent in the case of the single, and as much as 35 percent in the case of the twin. The turbine was not judged to be competitive in very small sizes such as the 140 SHP

required for a turboprop version of a Cessna 172. It just simply could not achieve the performance required in that size category. So the advanced turboprop would only be a candidate for the higher end of the singles market and the multi-engine twins. These results, comparing advanced turboprops with current recip engines, are only part of the story of course. Comparison with the various hypothetical advanced internal combustion engines is equally important and such comparisons were made in a NASA in-house analysis.* Results showed the turboprop to be competitive only above 300 SHP. Above 300 SHP, all of these candidates are worthy of pursuit.

If eventually it turned out that the turboprop was the only viable solution, one might then ask "What would that do to the fuel situation?" I think that is a legitimate "what if" type question. The shaded portion of Figure 3 shows the number of engines that are subject to turbinization. In 1979, turboprops accounted for about 1/20th of the production of all aviation engines. Most of the piston engines, of course, were produced around the 200-300 horsepower size. The potential of a hypothetical GATE-technology turbine engine is such that it could replace about 30 percent of piston engine production. One can conclude, therefore, that the alternative IC engines are complementary in nature to the advanced turboprop. However, the question is "What will happen in the absence of alternative IC engines?" Figure 4 shows our projections. The current G/A turbine engines, although very small in number, actually consume more fuel than avgas-powered aircraft do. Even without a GATE Program, that trend is continuing such that in several years we expect that avgas will represent only about 35 percent of the total general aviation fuel consumption. If there were a GATE turboprop in the future, it would occupy some of the marketplace and eventually would reduce the avgas portion of the total market to something on the order of 25 percent. Of course, these estimates are very rough.

We heard previous comments concerning flying piston airplanes into airports where they do not have avgas. The other side of the coin is "What happens if you take a turbine-powered aircraft into one of the small, general aviation airports and you don't find turbine fuel?" That would become an even more interesting question if the GATE Program were actually to be implemented and become successful. The problems encountered are summarized in Figure 5 and arise from the lead in the gasoline. Lead forms deposits in the combustor. These are severe with extensive and continuous use of leaded avgas in turbine engines. Tests have also shown intergranular metal attack of the hot turbine parts, which is detrimental to the life of those parts. Also, because of the volatility, low boiling point, and flammability limits of avgas, turbine engines are likely to suffer some flight envelope and starting envelope restrictions. These restrictions are not judged to be serious if one were to just use this fuel on an emergency basis. And lastly, if an aircraft does not have an onboard fuel boost pump it would likely suffer vapor lock or fuel pump cavitation problems. But most of the turbine-powered aircraft, of course, do have boost pumps.

The real show-stopper is the lead. If you got the lead out, there's no reason you couldn't use avgas in turbine engines today. The current status, then, is that turbine engines can use avgas on an emergency basis. They are certified to do so, in fact, for between 6 and 150 hours per TBO. You can sometimes even use avgas on a semi-continuous basis. For example, to cold start the Allison 250 small engine when Jet B is not available, avgas is allowed in a one-to-two mixture with Jet A. In fact, that procedure

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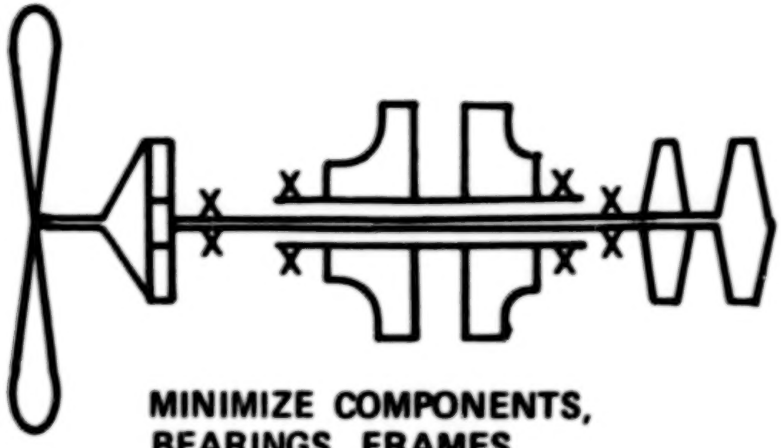
*Wickenheiser, T. J., et. al: Comparisons of Four Alternative Powerplant Types for Future General Aviation Aircraft. NASA TM 81584, Oct. 1980.

is recommended below 40°F. Avgas use usually requires an adjustment of the fuel control. For example, the pilot may open a cowl access door and reset a fuel density knob. In most cases it's not a difficult task. In days past, the fuel control systems have been limited in their capability to tolerate avgas when starting engines or for accommodating throttle bursts. The modern electronic systems can tolerate the acceleration schedule of turbine engines using avgas considerably better than the past systems. So the real show-stopper, to say it again, happens to be lead.

Finally, NASA has recently initiated combustor research for small turbine engines that addresses the capability to use the broad specification fuels we anticipate in the future. And I would add a recommendation that those studies be broadened into consideration of the possible use of avgas as well.

DESIGN SIMPLICITY



MINIMIZE COMPONENTS,
BEARINGS, FRAMES

NET SHAPE INTEGRAL COMPONENTS

LOW-COST COOLED TURBINE

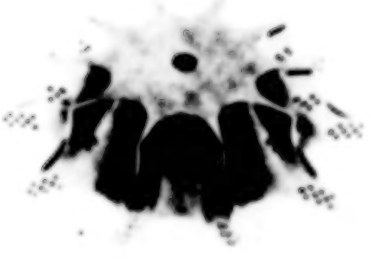


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Figure 1. - GATE approaches to low cost.

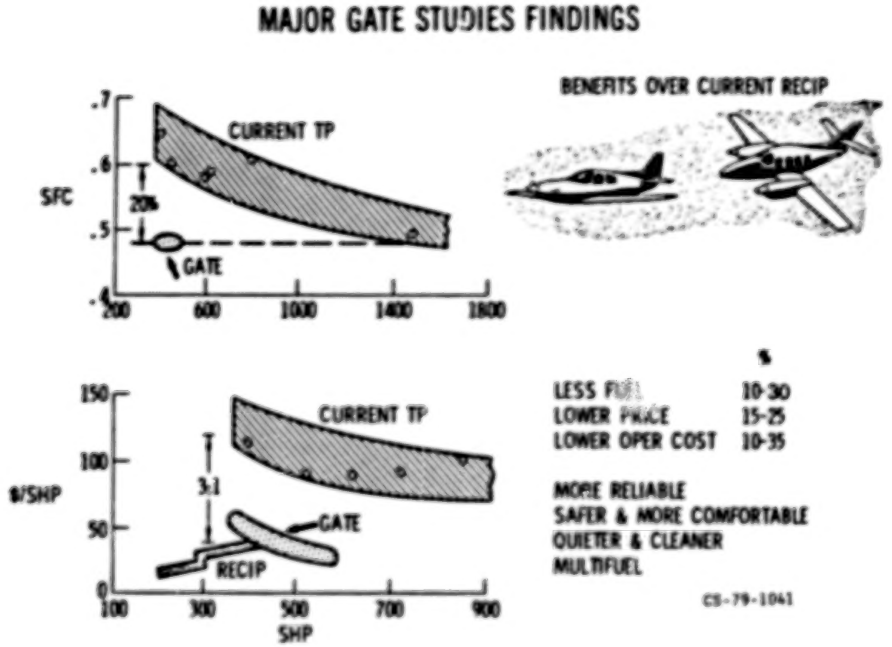

Figure 2.

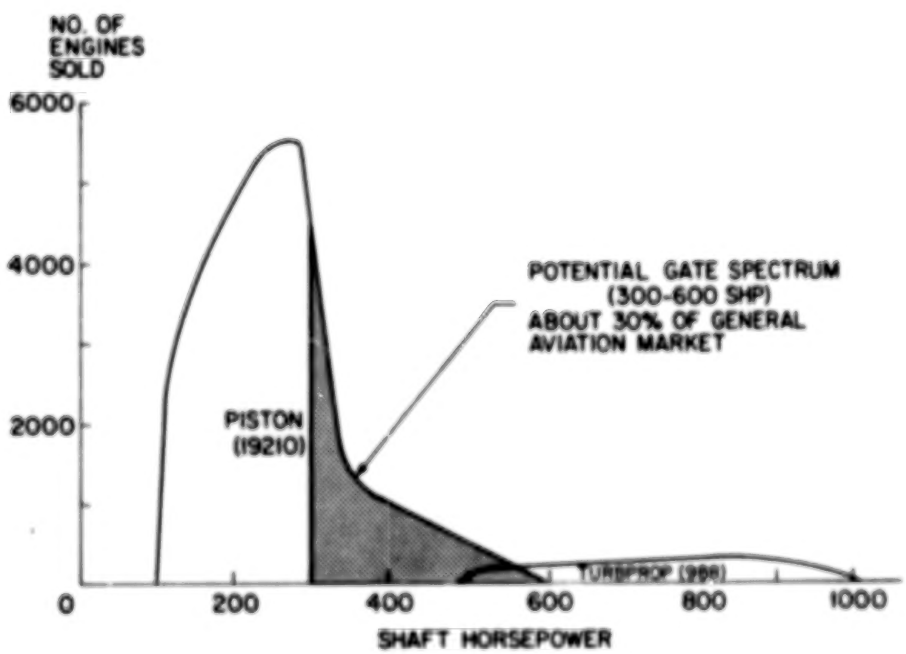

Figure 3. - Approximate engine sales in General Aviation, 1979. Data for U.S. manufacturers only, spares excluded.

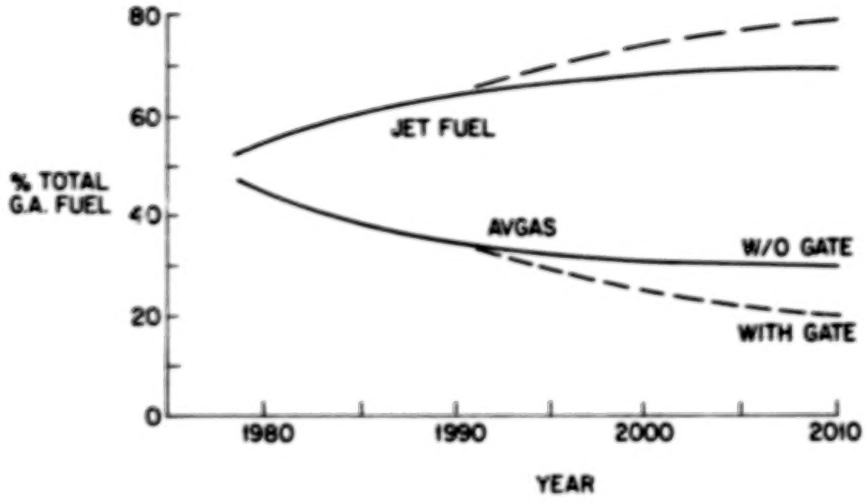

Figure 4. - Potential impact on General Aviation fuel.

TURBINE ENGINE TOLERANCE TO AVGAS

PROBLEM

- Forms lead deposits in combustor
- Intergranular metal attack of combustor and turbine by lead
- Shrinks flight and ignition envelopes (boiling/flammability)
- Requires fuel boost pump to prevent cavitation (usually onboard)

CURRENT STATUS

- Acceptable for emergency use (6-150 hr per TBO period)
- Sometimes permitted for semi-continuous use, e.g.,:
  - 250 gal. per 100 hr
  - Mixed with Jet A(1:2) for cold weather
- Usually requires density adjustment on fuel control
- Modern electronic fuel control systems accommodate AVGAS

FUTURE DIRECTIONS

- Combustor research aimed at heavy end of broad-spec fuels
- Recommend consideration of AVGAS as well

Figure 5.

CURRENTLY PLANNED NASA GENERAL AVIATION NEW INITIATIVES

Harry Johnson
NASA Headquarters

Part of our planning for the last two or three years has been an attempt to generate interest, call it advocacy, for a substantially enlarged program in general aviation propulsion. In addition to the GATE (for General Aviation Turbo-Prop Engine) program that Bill Strack just described, and the internal or intermittent combustion engine programs that Ed Willis described, we also have one that isn't going to be described in this meeting. That is our low speed propeller research in which the objectives are also improved fuel economy and some other attractive features including reduced noise and improved life and safety, aided by the use of composites.

We lumped these three research area expansions together as one general aviation propulsion program recommendation for inclusion in our budget. Unfortunately, we have not been successful in persuading the Office of Management and Budget to accept this augmentation as part of our program, and so it is not included in our Fiscal 1982 request. Nevertheless, we are still hopeful that in the future we will be able to have a significantly expanded program of the type that you just heard about, expanded in the way that is necessary to see some real results come out rather than the current, relatively low level, research and technology base programs that Ed outlined. Those can go on and on, and from them there may come incremental improvements and changes, but no significant new concept hardware demonstrations. In the end, realistic demonstrations of this sort are necessary to reduce the development risk and convince the industry and public at large that these engines should be developed.

I don't want to try to speculate too much about the future. We're facing the situation everybody appreciates, a new administration. We do not yet understand what the Office of Management and Budget's attitude toward civil aviation research will be. We don't know how the government's stepping back, not only from regulation and that side of the business, but also perhaps from research, will affect these programs. I'm not predicting a gloomy outlook necessarily; I simply do not know what to predict for support of this kind of work. We hope for the best. There's no point in trying to speculate further right now. I want to mention only one other point about this uncertainty, though, and that is the attitude of the new administration with regard to the nature of any government support for research and development of this type, if there is to be such. I refer to the issues of recoupment and industry cost-sharing. How they will affect our program planning has yet to be seen.

FAA ALTERNATE FUELS PROGRAM

Thomas C. Boreff
Federal Aviation Administration

Let me begin by supplementing my previous remarks in Session 1 concerning the procedures for approval of alternate fuels. The Federal Aviation Regulation and the amendments thereto that form the certification basis for engines and airplanes are established by the date when the engine and airplane manufacturer originally applied for certification. Consequently, when the engine or airplane manufacturer wants to obtain approval for alternate fuels or someone else wants to obtain a supplemental type certificate for approval of alternate fuels, he is legally required only to comply with the certification basis to which the original airplane and engine manufacturer complied. That is to say, if the date of application for certification was 1965 and someone wanted approval in 1981 for alternate fuels, they're required to comply only with the rules and amendments in effect in 1965.

Now I will discuss the efforts of FAA in the alternate fuels area. In 1976, FAA Headquarters issued an order to all the regional offices which prohibited the approval of supplemental type of certificates for the use of autogas because, as has been pointed out previously, there is no adequate specification which determines autogas at any specific location. There are 17 different geographical areas in the contiguous United States where the autogas is adjusted to suit the conditions in each of those particular areas. In each area, autogas is adjusted for seasonal variations also. When Professor Patterson compared the Reid vapor pressure of autogas with avgas in Session 1, he could have shown several more curves based upon the detailed data from the fuel surveys provided by the Bartlesville Energy Technology Center. When we reviewed the variations in Reid vapor pressure of all the fuels in each of the 17 areas for each season, we found a variation from 7 to more than 15 psi. Consequently, when the use of autogas is considered, the question is raised: Which autogas are we really talking about?

Another reason for prohibiting the approval of supplemental type certifications for autogas has to do with the lack of data related to the various potential short and long-term problems that should be solved before autogas can be used safely and reliably.

In 1979, the National Transportation Safety Board issued what was termed a Vehicle Factor's Investigation Alert concerning the use of autogas in aircraft engines. In this alert, they referred to a review of general aviation accidents between 1967 and 1976 which indicated that there were 16 accidents in which autogas was being used. They recommended to their field inspectors that in any accidents where autogas was used, the engine be disassembled and a detailed analysis conducted in order to determine whether or not autogas was, in fact, the cause of the accident. Between 1976 and 1979, NTSB released additional accident briefs which pointed out that there were 6 accidents in that time frame where autogas was being used. This gives a total of 22 then, since 1967. However, this does not mean that autogas was necessarily the cause of the accident, only that it was being used.

The investigative alert stated: "A careful perusal of the report revealed 16 accidents caused by autogas." Now when we (FAA) perused that report, we could not come

to that conclusion. There is a question in our minds whether or not autogas caused the particular accidents that are cited. Conclusive information is lacking.

Professor Patterson described the results of his work resulting from the 1979 award of a contract by the FAA Technical Center concerning composition and characteristics of autogas. That was only Phase I of the effort and we are now discussing with Professor Patterson what kind of testing would be appropriate in Phase II of the work.

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15. Supplementary Notes

Donald J. Patterson: University of Michigan, Ann Arbor, Michigan.

16. Abstract

A three-day technical workshop was held at the NASA Lewis Research Center in February 1981 to consider the problems surrounding the use of aviation gasolines in light aircraft and possible technological solutions thereto. Approximately 90 high-level attendees represented virtually every facet of the general aviation community. It was concluded almost unanimously that any completely new general aviation engine should be designed to burn commercial jet fuel (Jet-A and future broadened-specification versions thereof) as the fuel of choice. This consensus was accepted by NASA as establishing the basic direction of its general aviation engine R&T activities for the foreseeable future. Summaries of the workshop's principal observations, conclusions, and recommendations have been published in NASA TM-82869 and SAE Paper 820718. This report contains the complete proceedings of the workshop, including transcripts of all individual presentations and related discussions on industry needs and directions; fuel supply, demand, and distribution issues; technological prospects; and ongoing or planned NASA programs.

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